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DEVELOPING A FRAMEWORK FOR PREFABRICATION ASSESMENT USING BIM

Final Project of the degree of Industrial Engineer in the programme of Industrial Technologies

Supervisor: Professor Vishal Singh

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Building Information Modelling is a disruptive technology in construction at this precise moment, and the opportunity to take advantage of the technology by combining it with prefabrication should not be wasted.
The adoption of BIM represents a complete revolution in the construction environment, since it changes construction processes in every aspect. The purpose of this project is to present the prefabrication components clearly, for relating them with the most conceptual and theoretical concepts used in construction. This will help the designer for the design of building components. Then, BIM benefits are presented with the potential of using this technology.

Designing a component is only the first step in prefabrication procedure, since the manufacturing process can seriously affect to the whole construction process. The different techniques are explored, paying special attention to 3D-Printing and Contour Crafting. One more time, these technologies align with prefabrication principles.
In order to achieve the highest efficiency in the construction process, methodologies such as Buildability, Function and Structure Sharing and Mass Customization are presented, as well as their possible implementation in the construction field.

Finally, some real case studies which employ prefabrication methods are studied and analyzed according to the framework and the statements made before. The project also proposes some recommendations for those who plan to conduct such studies in future.

Keywords: BIM, prefabrication, component, 3D-Printing, Contour Crafting, Buildability, Function and Structure Sharing, Mass Customization	Publishing Language: English Number of pages: 121

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Título: Developing a framework for prefabrication assesment using BIM Autor: Carlos Cereceda Fernández Deparmento: Department of Civil and Structural Engineering	Supervisor: Vishal Singh Cátedra: Computer Integrated Construction

Building Information Modelling es una tecnología completamente nueva actualmente, y por lo tanto es clave la necesidad de explorar nuevas oportunidades y potenciales de dicha tecnología. Por ello, el estudio de la prefabricación en dicho entorno se plantea como altamente interesante.
Es necesario aclarar que BIM supone una revolución completa en la manera de llevar a cabo los proyectos en construcción y por ello es necesario tener claros los conceptos más básicos desde el principio. La primera parte del proyecto incluye una descripción teórica de los tipos de materiales y componentes prefabricados existentes.

Posteriormente, se explica en detalle los conceptos y terminologías empleados en la industrialización, lo cual será clave para entender todo el marco conceptual posterior. Los procesos de fabricación tienen vital importancia en este caso, por lo que se estudian aquellos que están especialmente alineados con los principios en los que se basa BIM, en concreto la impresión 3D y Contour Crafting. Puesto que el objetivo es alcanzar la mayor eficiencia en el proceso constructivo, se presentan conceptos como la Constructabilidad, la personalización en masa o la compartición de funciones y su posible implementación en la realidad.

Finalemente, se muestran ejemplos reales de empleo de materiales prefabricados y se analiza en qué lugar se clasifican dichos procesos en el marco conceptual desarrollado a lo largo del proyecto. Se incluyen recomendaciones constructivas y valoraciones personales en base a lo observado durante la realización del trabajo.

Palabras clave: BIM, marco, industrialización, Contour Crafting, impresión 3D, constructabilidad, personalización, compartición.	Idioma de la publicación: Inglés Número de páginas: 121

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INTRODUCTION

1. Introduction

1.1 Aim of the project

Is it possible combining prefabrication methods with BIM technology? Which should be the correct practices in order to achieve efficiency in construction? How could be the efficiency of the construction process improved? Do I have clear the differences between all the building concepts? Which is the best manner for building prefabricated components with BIM technology?

Here are some of the questions that the reader could ask himself before reading the paper, but not answer. The main purpose of the paper is to create a solid conceptual theory about the implantation of prefabrication within BIM environment, while explaining the benefits of the practice. By taking full advantage of the benefits provided by BIM and introducing measures to improve industrialization of the process, I would like to achieve the implementation of prefabrication benefits in the whole construction process.

This paper is focused for people with low expertise in prefab environment. Because of that, the simple explanation of basic concepts at the beginning leads to the creation of conceptual relationships with other terminologies.

As I stated at the beginning, the project will not present specific and numeric results, but it will be a guide for understanding and linking the concepts, especially helpful for people whose desire is introducing themselves in design of BIM prefabricated components. Also for those students who would like to introduce themselves in BIM design is helpful.

Finally, contributing with prefabrication-related knowledge useful for the BIM community is one of the highest goals, because of the necessary revolution that must be taken in constructing methodologies and the huge contribution made by many researchers all around the world.

1.2 Research Objectives

The main objectives of the research will be presented now:

- Providing a solid conceptual basis for understanding prefabrication-related concepts and to develop the conceptual framework.
- Serve as a basis for further prefabrication research, mainly related with design advices for BIM environment

- Helping people with low knowledge of prefabrication to introduce into the topic and to establish the relationships between BIM and prefabrication environment.
- Researching into new constructing technologies which may provide great opportunities to combine prefabrication methods with BIM.
- Improving the global efficiency of the constructing process, by suggesting the introduction of new methodologies.
- Understand how the theoretical, virtual and real constructing worlds are connected and which the methodology for taking advantage of the benefits is.
- Studying the limitations for the implementation of each methodology and defining a clear path for applying the theory in a real case.
- Provide examples about which current practices of manufacturers are and how do they compare to the framework.

1.3 Background of the study

The apparition of computer technology has supposed a whole revolution in every manufacturing industry. The natural tendency is to achieve much efficient processes combined with high environmental respect and quality.

But there is an exception in the construction industry, where the adoption of digital industrialized processes has been much slower, due to the reticence of customers and false sensation of “low-quality construction” when using the technology combined with prefabrication.

Therefore, due to the variety of new opportunities provided by BIM software and its alignment with prefabrication principles, developing a framework to understand how both technologies can be combined to achieve better products is necessary. Especially for Spain, where the implementation of these technologies is even lower than other countries, the introduction of the framework could be a great opportunity for local constructing companies.

BIM is known for combining the advantages of parametric technology with 3D visualizations with scheduling and cost dimensions. Therefore, some of the advantages are clash detection, obtaining clear and detailed 3D visualizations beforehand or achieving high precision when designing.

But it also introduces a completely new aspect, which is the possibility to combine management and construction calculations for achieving the integration of all building information to create a virtual building environment. This leads to new problems because of the required collaboration between the different actors involved in the process.

Therefore, the combination of an industrialized component with BIM technology sounds adequate: an industrialized construction process requires high-skilled labor, for creating components with low-tolerance level, and that technical labor and high-precision components is what BIM industry need for taking the next step forward.

From the first moment I started looking at prefabrication literature, I could notice the misconception in the terminologies employed, confusing industrialization with preassembly or standardization. Because of that, after reading the existing literature, I had the obligation to explain the concepts clearly to notice the differences and to stablish a clear differentiation in terminologies.

The methodologies to improve efficiency, such as buildability or mass customization have been largely studied along the years but they have focused on onsite construction methods or traditional prefabrication ones, lacking of approach to new manufacturing techniques (3D printing).

Because I truly believe in 3D printing potential as a construction process, I have focused on the study of this according to the concepts explained before and analyzing its potential within the framework.

1.4 Research Methodology

The study was driven to assess the benefits and challenges of implementing prefabrication products within BIM technology. For this reason, the project uses descriptive method of research for understanding the current state of the technology based on the available literature and publications. The information has been obtained though “Google Scholar” and the available bibliography in Aalto´s University Library.

After a deep read of the content, the main ideas are taken and structured to clarify the concepts. Then, my own input is provided by relating the concepts obtained with the previous ones.

Since this is a conceptual framework, at a first time clear ideas about prefabrication fundamentals were required. After that, I started building my own relationships and definitions based on industrialized building terminologies so I could relate them with prefabrication fundamentals. Then, the BIM literature was introduced, and after presenting all the theory, the relationships where established with the prior concepts.

After the explanation about how are the different terminologies related between themselves, the different construction techniques were exposed leading to the creation of a basic framework, in which the manufacturing technologies were presented and evaluated, paying special attention to 3D Printing. This framework is completed by including methodologies for increasing the efficiency of the construction process and which are aligned with BIM principles.

Throughout the paper I have created my own explanatory charts in order to clarify the connections between the concepts and to ease the understanding.

The scheme for the development of the ideas is the following:

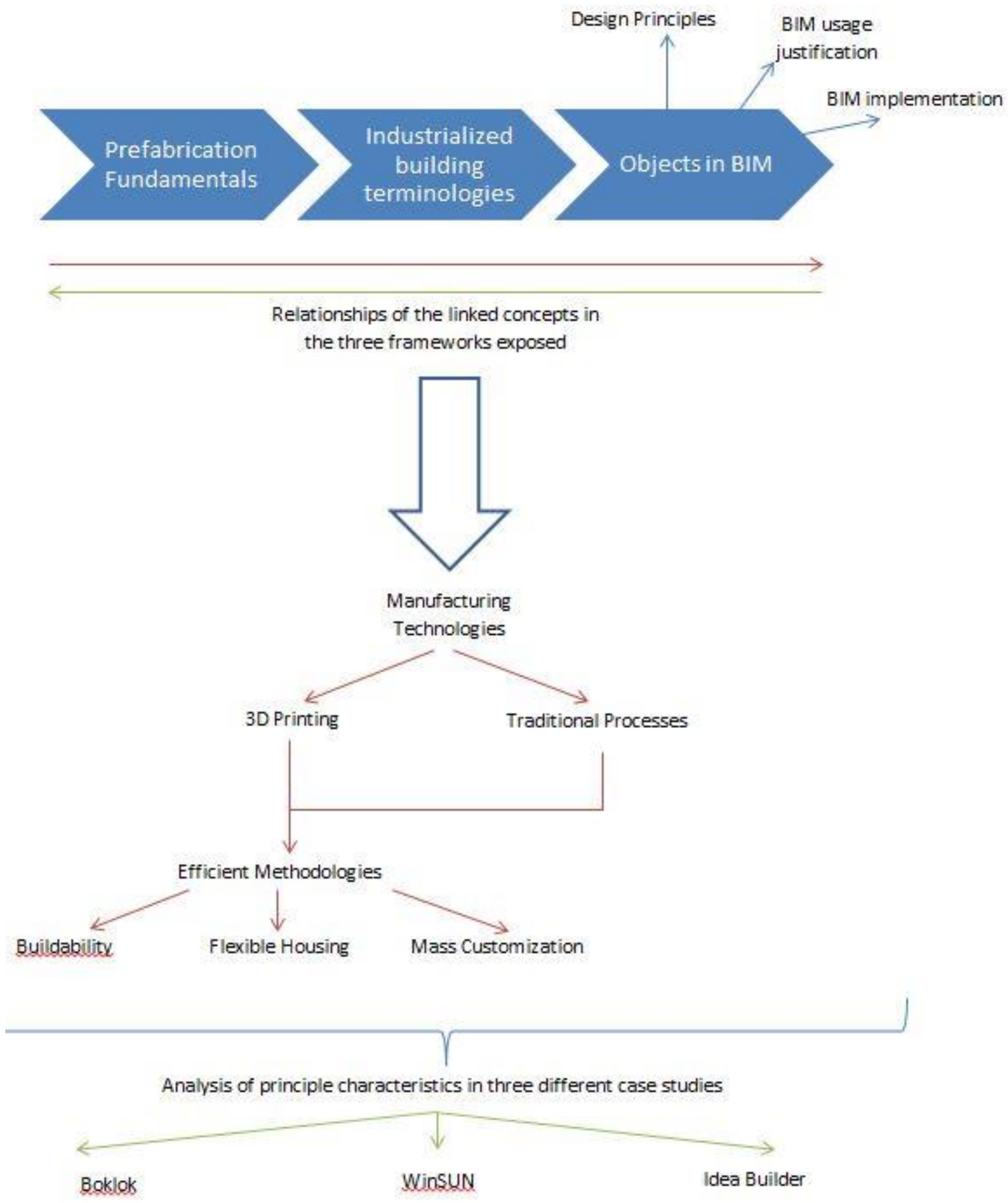


Figure 1: Research methodology carried out in the development of the project

The case study methodology has also been used by studying the available online documentation of the different companies. Since the projects were made some years ago, it has been possible to notice the differences between the prior state of the technology and the current one. One more time, the different cases have been evaluated according to the framework created at the beginning by combining BIM, Industrialized building terminologies and fundamentals of prefabrication.

1.5 Data Collection

The purpose of this project is stablishing a conceptual framework for assessment in the introduction of prefabricated materials within BIM environment. None experiment or survey was developed and therefore, none result is acquired from these. The data was only collected from written bibliography (both online and printed).

1.6 Motivation and Significance

On one side, the possibility offered by Aalto University and the Professor Vishal Singh has been a wonderful opportunity to apply the concepts learnt along these years in Spain and to prove myself that I could adapt to a completely new environment.

On the other side, prefabrication has always fascinated me, and since engineers always look for the optimization and efficiency of the processes, the chance for implementing prefabrication within BIM technology is a great challenge. I have always wanted to know how researching is and although there were some tough moments; the final result is worth it.

One of the main reasons for doing this project is the current situation of construction methodology in Spain. Since 2007, Spain is immersed in one of the biggest crisis ever. This crisis has been especially cruel for the construction industry, which was one of the most important ones in terms of economics.

Thus, the possibilities for working in construction industry are small. In addition, Spanish population has always been reticent to introduction of new construction methodologies and prefabricated materials. Because of that, I think it would be a great opportunity to introduce BIM principles combined with prefabrication, especially in civil construction, in order to improve the high expertise that many Spanish companies have.

Also contributing to help the research in BIM is an honor for me, especially when working with Professor Vishal Singh and his department, who have been supporting and advising me in every moment.

1.7 Limitations of the project

This is a conceptual project, and it is not based on measurable figures. Because of that I can just study the concepts, understand and conceptualize them in order to ease the understanding.

Obviously, the highest limitation is the one imposed by the theoretical nature of the project. Everybody knows the big difference made from the theory to the application of the concepts in the reality in any methodology, and this is not an exception.

Other limitation is the lack of connection of the project with specific BIM software, like REVIT or TEKLA. For that reason, I would recommend the continuation of this paper by researching within the software.

Since all the information obtained comes from written bibliography, it would have been interesting getting the information of the case studies from the manufacturers themselves. If I had the opportunity to collaborate with them, I could have known their personal feedback about the positioning of their methodologies in the theoretical framework, and how they feel about the current state of the technology.

1.8 Structure of the project

In many writings, BIM is argued to be a catalyst for change and the necessity of a framework is obvious: as an early technology, delineating and subdividing all the aspects promotes understanding, helpful for people who are not especially acquainted to BIM environment and willing to contribute to research.

The first part of this document focuses prefabrication fundamentals, from materials to different types of components. This part is purely theoretical, since it just tries to present the information in a summarized manner.

The next section is the most important one of the whole project, and includes the conceptual definition of industrialization-related terminologies. It will help to determine how each element is classified and how is it considered in the further explorations. It is also important seeing the correspondence between the virtual (BIM) world and the real one and how each industrialized element does relates with a virtually designed one, and with the theoretical framework developed. Since prefabricated materials are highly related to flexibility and modularity concept, a further research is made in this aspect.

Once all the concepts for virtual design are clarified, it is time to have a deep look at construction techniques. Since the project tries to focus not only in the actual state of the technology, but also in the near future, 3D printing research is important. As a constructive process, it is the clearest connection between the virtual and the real world, because both designing and constructing processes are integrated in the same technology.

Other important objective of the project is changing the concept that most of the people in Spain have with prefabricated and industrialized components. They are seen like low-quality, non-variable and originality lacking components. For that reason, mass-customization, flexible housing concepts are studied, with the support of buildability concept.

Within the theoretical framework, it is important defining structure sharing and function sharing concepts. By relating these terminologies with pre-assembled components, we will understand better how each building component can be decomposed from the highest complexity level to the lowest one.

Finally, some case studies are evaluated according to the framework developed, not in every aspect, but in the most relevant ones. The conclusions try to summarize the main ideas in the text and help to understand better the whole content of the project. There is a final chapter with my personal conclusions, the limitations and major problems for implementing the framework.

FUNDAMENTALS OF PREFABRICATION AND MATERIALS

1. Starting with prefabrication: Basic structural concepts for prefab systems

Constructing with industrialized methods is not completely different than doing with traditional ones. Because of that, the logical design procedure does not change and must include these four phases:

- Load Assessment: Estimating the load
- Calculation Model: Define the structural system, describing a possible load path and evaluating stiffness of components and joints
- Structural Analysis: Determination of loads on components and joints
- Documentation

In general terms, vertical loads comprise the dead weight of the structure. Load from lightweight partition walls i normally treated as a line load. Horizontal loads are derived from the wind forces.

A building constructed from precast components becomes a fragile and requires rather simple structural calculations as most of the load bearing structural members are considered simple supported.

Using precast floor slabs, walls, beams and columns, it is seldom possible to achieve restraint in the joints, due to small dimensions of the components.

Systems with load bearing cross walls, spine walls or façades are more suitable for domestic housing, apartments and hotels. They are faster to build, are ready to be painted and you get good acoustic insulation.

Load bearing façades are often used in combination with skeletal frames as internal structure. These systems are economical, have a high construction speed and can incorporate architectural finishing.

Cell systems are mainly used for some parts of the building, such as bathrooms, kitchens…

Structural joints can be grouped into hinged or pinned or fixed points and can be prefabricated of formed at site. By manipulating joints and their positions various structural frames can be achieved from the assembly of precast components.

It´s recommended that prefabrication together with the extensive use of standardization and modularization should become essential principles in the design and construction.

2. Principles of prefabrication

This part tries to present briefly the existing prefabrication theory, based on the existing book *Prefab Architecture: A guide to modular design and construction* (Ryan E. Smith; 2010), for making further relationships between these concepts and the future ones.

According to *Prefab Architecture: A guide to modular design and construction* (Ryan E. Smith; 2010), four different principles must be taken into account when considering prefabrication:

- *Cost*: Prefabrication known to be much more cost efficient than other onsite methods of construction. This is because cost consists of three aspects on which prefabrication has an impact: material, labor and time.

  The first option to reduce cost is to reduce the amount of material implemented in a building project. In an on-site construction, materials are over-ordered to ensure an adequate quantity for the task.

  Although prefabrication may save considerably with regard to delivery and staging of material, factory produced components may initially be more expensive. Especially on small projects, due to the short-run amount of components, it is economically unfavorable.
  Other costs that may be incurred with prefabrication include transport expenses. Although prefabrication requires larger trucks for transport to site, coordination and transportation for onsite construction does not take into consideration the daily trips to pick up forgotten materials.

  Placing the cranes at the onsite place is expensive, and cannot be avoided by using prefabrication. Traditionally, it is not as expensive as with onsite techniques since the construction period is shortened.

- *Schedule:* Again, construction period is shortening is good for another principle. The savings come in the ability to simultaneously construct in the factory while site work is being completed. In traditional onsite construction processes, subcontractors have to wait until the precedent trade has completed its work, in a factory, teams may work together allowing sections to be constructed by more than one trade.

  Time savings may also come by way of employing lean production techniques. Decisions regarding prefabrication are made early so that schedule savings may be realized from the start of construction.

- *Labor*: Productivity is a measure of efficiency in labor. With offsite fabrication, technical changes including machinery in the factory, evolutions in material science and digital revolutions like BIM have positively impacted the productivity of labor in construction. Some of the means are:

  - Amplified human energy to increase output
  - Increased levels of control, precision and accuracy
  - Added variability to production manipulation
  - Improved ergonomics to reduce fatigue

- *Quality*: There are two concepts to evaluate quality; quality of production and quality of design (associated with the work of the architect). As soon as production quality increases, architecture becomes more standardized, while a highly customized design inevitably suggests lack of production efficiency.

  Prefabrication requires the creative abilities of architects, engineers and fabricators to create a method to increase both quality of design and production.
  Onsite construction is still a handcraft culture in countries like Spain, opposite to other industries, which use automation and precise methods of production.

  Obviously prefabrication can increase the precision of the products and allow a greater control over each element. Along with increased precision is the ability for manufactured components to have less dimensional tolerance.
  Prefabrication limits the risk of errors and eliminates the unknowns in a highly multivariable construction.

Here there is an interesting chart comparing prefabrication and onsite production in many different aspects of the principles seen above:

PRINCIPLES	**OFFSITE**	**ONSITE**
Cost		
Transportation	Two stage delivery: shop and site	Raw material delivery
Change orders	Extra cost and delay	Accommodated changes
Material	Less scaffolding, formwork and shuttering	Increased scaffolding, formwork and shuttering
Craning	Costly heavy duty cranes	No cranes in small projects, large stationary for big ones
Initial cost	Higher investment in product	Lower initial costs
Lifecycle cost	Great savings in lifecycle	Higher maintenance requirement
Profit	Savings from scope, material may not be passed to the customer	Overhead fees are more transparent to owner
Lean	Reduce time waste increases value	Lots of wasted time
Productivity	Full 8 hours of work	Productivity increases difficult

PRINCIPLES	**OFFSITE**	**ONSITE**
Schedule		
Duration	Finish date up to 50% reductions	Overruns are common
Scope coordination	Extra coordination needed	More time for coordination and opportunity to adjust dimensions
Schedule reliability	Long lead time, reduced erection time, reliable duration	Shorter lead time, longer construction and less reliable
Weather	No problems with weather	Delays due to weather
Work flow	Concurrent scheduling	Linear process
Subcontractors	Fewer conflicts	Simultaneous trade crowding difficult
Supply chain management	Coordinated	Uncoordinated and wasteful

PRINCIPLES	OFFSITE	ONSITE
Labor		
Local labor	Less local labor needed	Local labor needed
Working conditions	Improved working conditions and more stable job market	Variable working conditions
Unskilled labor	Supervision of labor, quality control process	Unsupervised labor leads to portions of project being reconstructed
Safety	Reduced exposure to accident	Accident prone job site
Skilled labor	Less chance for skill development	More chances for skill development

PRINCIPLES	OFFSITE	ONSITE
Quality		
Reliability	More reliable quality	Less reliable
Design	Integrated design and construction process	Separation of design and construction
Production	Predictable output	Difficult to anticipate
Regulatory	3rd party verifiers	Local jurisdiction with varied experience
Design Flexibility	More restricted	More freedom
Joining	Fewer joints, but difficult to detail	More joints, more potential to failure
Tolerances	Not forgiveness in module on site	Forgiveness with details constructed on site
Fit	Fewer points for water and air infiltration	More locations for infiltration

3. Structure of Prefabricated elements: structure and skins

3.1 Structure

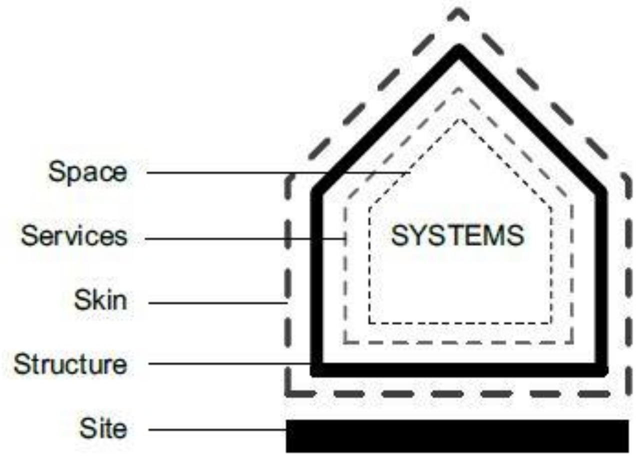


Figure 2: Structure of a prefabricated system [7]

According to *Prefab Architecture: A guide to modular design and construction (*Ryan E. Smith; 2010), structures are load-bearing and lateral-resisting systems that transfer dead loads induced by the gravity on the mass of the building and live loads induced by habitation, rain, snow…to the ground. Structures include foundations, frames, load bearing-walls, floors and roofs.

There are two possible structure types:

- Mass structures can be solid-bearing to transfer load not though distinct elements, but though surfaces and solids. Mass structures are built of stacked wood, laminated wood, concrete, or stressed skin panels in metal or wood.

- Frame structures: They act as skeletal systems made of wood, steel and reinforced concrete (materials which are strong enough to resist both tension and compression stresses. They are the most common due to their flexibility.
  These structures are composed of vertical columns and horizontal spanning elements such as beams or girders.

  Frames are inherently gravity load bearing, but they don't work well with dynamic loads as wind or seismic ones. As a result, they require a lateral load-resisting system:

- Brace frame: The junction of column to beam can be laterally braced with diagonal members of steel.
- Shear wall: They provide lateral resistance to horizontal loading. They infill bays between columns and beams.
- Rigid frame: Most frame structures are separated from enclosure. Frame load-bearing structures can be framed in a variety of relationships with infill such as inline, online or offset.

3.2 Skin

This element mediates between interior and exterior environments. The protection from exterior extreme temperatures and elements is the primary function of an enclosure system. [7]

Exterior skins must perform also a variety of tasks, and all of them must be fully considered to create architecture that responds to the needs of inhabitants.

- Function
- Construction
- Form: aesthetics of the building skin
- Environment: Performance of the building skin in lifecycle.

Construction and design are inseparably linked as structure and enclosure design determine the visual appearance of the building. Load bearing components such as beams, supports and walls define the division and proportions of the building skin.

We can classify building skins according to the following criteria:

- Load transfer (bearing and non-load-bearing): Bearing skins include traditional structures. Non-load-bearing transfer are the most common structures today and separate building structure from the exterior enclosure skin. They are composed of wood, glass, metal, ceramic or stone.
- Shell arrangement (single-skin or multilayered)
- Transmission (transparent, translucent, opaque)
- Structure-enclosure-space relationship: The integration of these elements has an impact on one another. Spatially, building skins can be placed in front of, behind, or in line with the structural systems of a building.

Prefabricated façades consisting of panels of wood, glass, metal, stone or precast cladding are multilayered and multi-material with each layer performing specific functions, such as air infiltration, water protection or thermal transmission.

4. Prefabrication from management point of view: lights and shadows

A good management implies a good communication between different actors of the project aimed to increase the quality of realization and work conditions. As a result, prefabrication allows centralization of the project in the factory. Much more involvement between architects and engineers is required.

Based on [2], I will try to summarize all the advantages of prefabricated components in some points:

- Prefabrication allows being independent of the weather conditions, as precast concrete is made in highly ambient conditions. Since delays are one of the biggest problems in building, lot of money is saved. One clear example is concrete setting, much more difficult when done onsite.
- Prefabricated components are built with strict control, which includes temperature regulation, specific position and other factors, like an adequate protection against corrosion.
- The actors involved in the construction process is reduced and manageable in an easier way.

Another important improvement from the management point of view is the speed execution. As we said before, there are fewer subcontractors and prefabricated products arrive ready for installation. On the other side, cast in-situ implies formwork and shoring that explains overtime.

The time taken to construct a building with precast reduced compared with in-situ cast, as modules may include insulation, electrical installation and exterior cladding, avoiding the intervention of subcontractors.

But there are also limits in prefabrication management. As we said before, prefabrication has traditionally only been profitable when the shapes of the building are simple and they are repeated many times. This is one of the main problems that I have observed, the impossibility to customize the product while industrializing it.

Once the production is over, the elements are usually stacked in a yard close to the construction site. It makes sense transporting of maximum number of elements in a single trip. As prefabricated components are usually big and heavy, large trucks are required for transportation.

The movement of wide loads requires exceptional authorization by the traffic department, which means that management will be more difficult compared to in-situ cast. Larger cranes are also required. Erection is made with cranes.

5. Fundamentals of Prefabrication

Again, based on *Prefab Architecture: A guide to modular design and construction (*Ryan E. Smith; 2010), categorization of materials, components, panels and modules is an organizational method to describe the degree of completion of a prefabricated element before arriving onsite. As we will see now, there are four different categories attending to the degree of finish:

5.1 Types of Prefab Materials

Today there are more choices of materials than ever before. With the advent of nano-materials and composites, the traditions of concrete, wood and steel may seem historic.

However, these materials are still high performers for their cost and the reality is that alternative structural materials seem unlikely in the near or long-term future. Now we will look at the most common ones:

- Wood: Although not common in the United States, wood in Europe and Scandinavia can be seen in products such as entire laminated wood panel walls that are structural and used for enclosure.
  In all of these applications, wood today is used primarily in components, individual pieces of lumber placed together onsite to make walls and then sheathed to provide lateral and gravity load strength.

  Wood is slowly but surely being used to develop prefabricated elements as well, such as entire exterior wall panels, with characteristics such as waterproofing, vapor barrier, insulation…
  Prefabrication in larger timbers, panels, and modules allows the efficiencies of construction while increasing the quality of the manufacturing process.

- Steel/Aluminum: Ferrous metals contain much iron, which rust and other inconveniences. They are used widely in construction, because iron is accessible and available everywhere.
  To solve the corrosion problem, ferrous metals can be treated with coats and galvanized.

  Nonferrous metals are less accessible than ferrous ones but they are natural corrosion resistant. These metals are not used in structural applications, but employed for cladding, roofing, enclosures, and other weather-exposed applications.

Mild steel, a nonferrous alloy, is primarily used as a structural material. The difficulty of welding steel connections onsite naturally requires fabrication in a factory. It is an expensive material when compared with wood and concrete, but strength to weight serviceability is superior.

Aluminum is not used as structural material. However, it is having a great impact in prefabrication. It is used for prefabricated panels and modules, and is able to be assembled, shipped and erected quickly.
Metal alloys are also used for lightweight cladding applications.

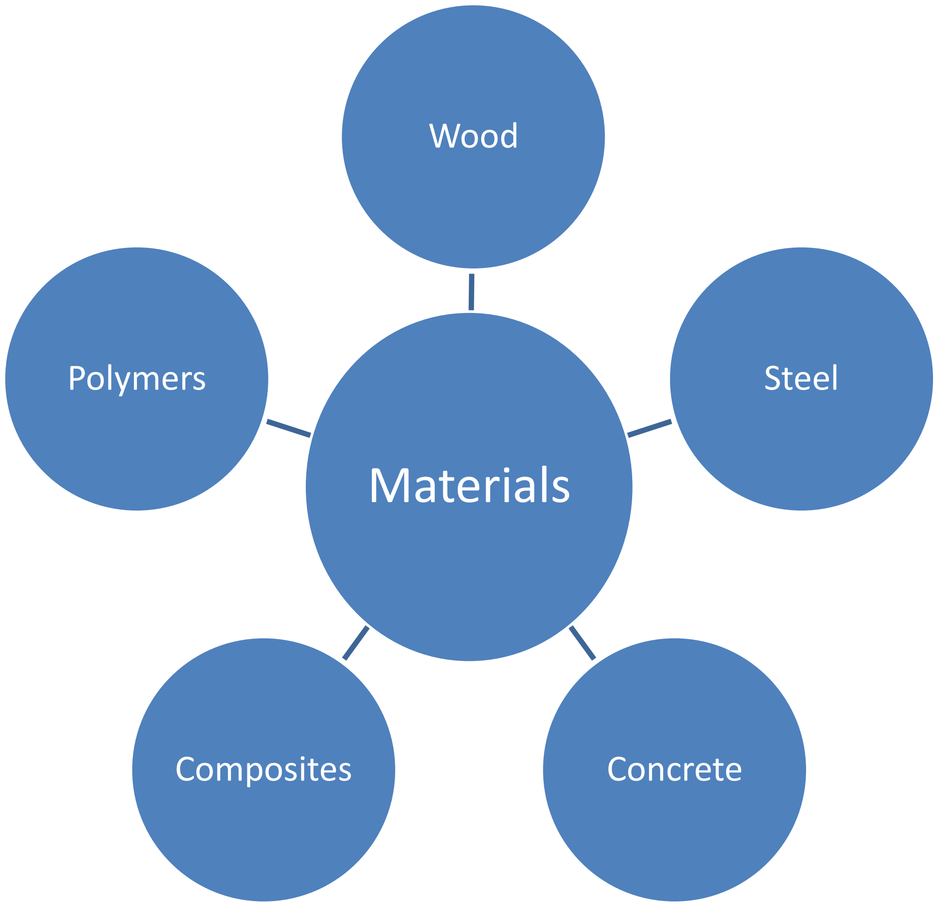


Figure 3: Materials used in Prefabrication

- Concrete: It is a versatile material, because it can adopt any formwork. The price is also really affordable, but requires a huge amount of labor to produce. Concrete resistance has increased during the last years, because of the inclusion of two additives:

    - Particle inclusion: Aerated autoclaved and fly ash inclusion.
    - Composite: Introduces reinforcing to the concrete matrix to change the properties of the material.

  Composite concretes are ideal for applications in cladding material, structural material and many other uses in which prefabricated elements can be produced in a controlled factory.

- Polymers: There are two types of polymers in existence:

    - Natural polymers: Are made from rapidly renewable resources such as rubber trees and soy plastic.

    - Synthetic polymers: Produced from oil, they can be sub-divided into 3 minor groups:

        - Thermoplastics: High degree of plasticity and can be reformed by heating during processing.
        - Thermoset: The polymer becomes permanently hardened when heated or cured.
        - Elastomer: Used because of their superior elastic range. They are used as sealants of exterior barrier walls.

  Prefabrication can employ all these polymer types within the factory environment to develop elements of components, panels and modules. They perform as barriers, sealants and adhesives, but require a great care in its installation.

- Composites: Composites are the combination of two or more materials to modify the properties of both. There is a base material which provides the primary material properties, while the other material is introduced to modify performance.

  The most common types of composites are concrete matrix composites in the way of glass fiber and carbon fiber reinforced concretes. The process of manufacturing elements in composites determines the strength and purpose of the composite.

5.2 Prefabricated Elements

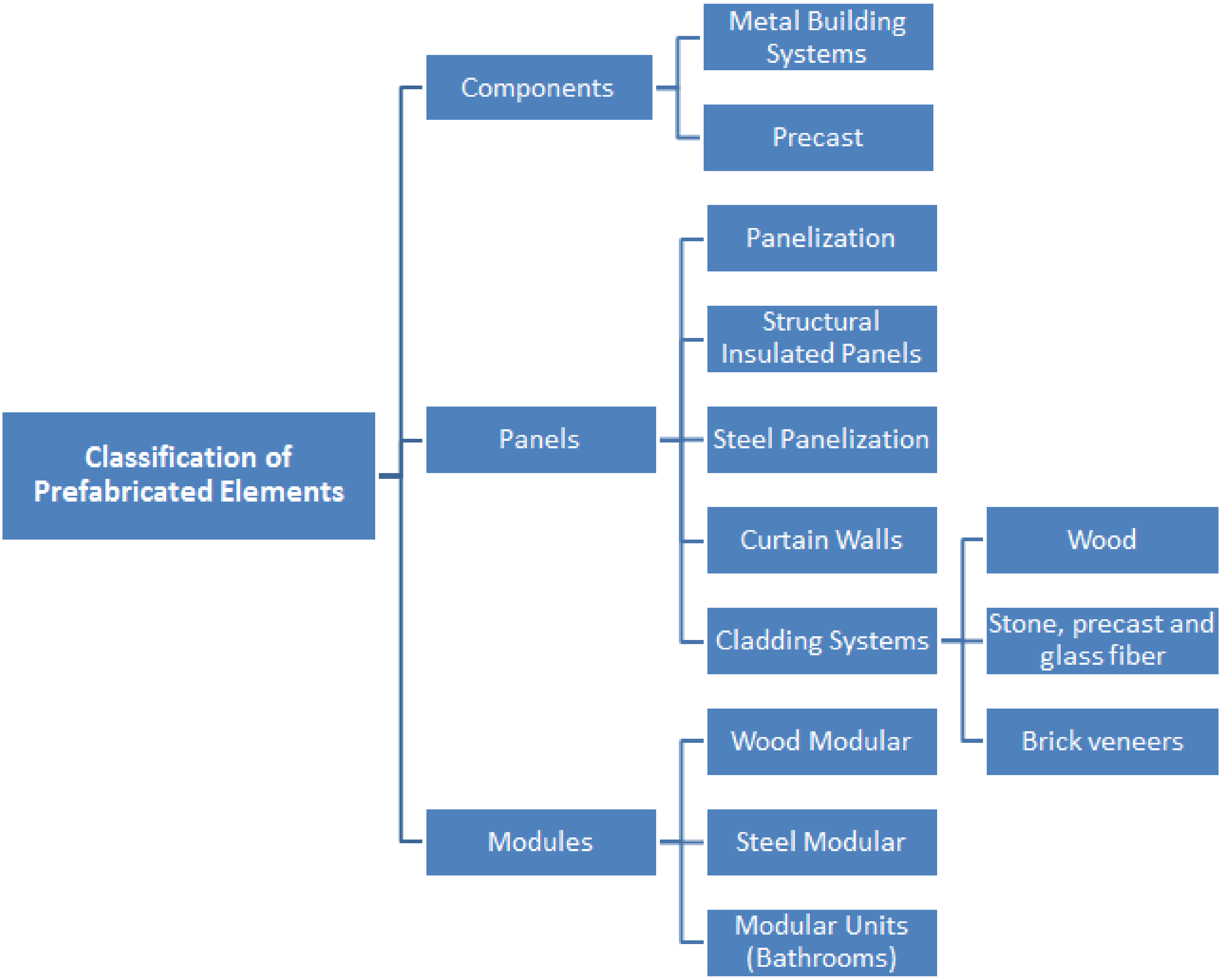


Figure 4: Classification of Prefabricated Elements

5.2.1 Components

Componentized prefabrication allow for the greatest degree of customization and flexibility within the design and execution phases. Components became numerous and are difficult to manage, so using BIM environment, especially with componentized elements for structure and enclosure, helps to improve the performance.

Componentized systems also require more joints, connections and as a result, more chances to misalignments, water filtration and other problems. Based on [7], components are:

- Metal building systems

  One of the major benefits of metal building systems is the research that has been developed to size and detail the steel, its manufacturing, digital-to-fabrication process, shipping and install. Benefits of metal building systems include a deep cavity between structure and exterior and interior surfaces, which allows for large amounts of thermal insulation to be placed in the envelope cavity.

  There are two major components of metal building systems:
    - Structure, including superstructure frame
    - Exterior enclosure with panels.

  The primary structure of a metal building system is a frame. The types of framing are categorized as follows:

    - Single-span rigid frame: No interior columns
    - Tapered beams: Moderate clear spans, straight columns and tapered girders to maximize depth at mid-span.
    - Continuous beam: Post and beam, interior columns, more economical.
    - Single-span truss: Same as tapered and continuous beam, but roof is supported by trusses rather than girders.
    - Lean-to: Relies on adjacent structures for lateral loads.

- Precast: When using concrete construction, the selection of precast over site-cast has lots of benefits. The vast majority of precast concrete today is pre-stressed, although it's possible also post-tensioning process.
  This is used in long span-beans, girders and tall shear wall applications.

  Special actions may be required to protect steel at joint conditions from corrosion. Methods for joining precast are in continual development: Joining is performed by the precast elements having weld plates with anchors cast at the plant.

  Besides joining precast components together, other components such as wall panels, facings or interior partitions must be attached to the precast elements. There are three categories of attachments:

  - Embed
  - Epoxy set
  - Expansion anchor

  The erection of precast is similar to steel. Another advantage is that precast can be shaped to form virtually any three-dimensional shape.

5.2.2 Panels

They are planer elements used to build structural wall, floors roofs, load or non-load bearing enclosures and interior partitions. We can classify the panels in [7]:

- Light panel systems: They are the most common panels, because of their numerous advantages:

  - Offer factory integrated wiring and cable utilities
  - Are designed to make utilities accessible after construction without damaging the panel.
  - Plumbing pipes usually run through the partition walls inside de house.

- Panelization: These are framing of light wood or light gauge-metal-framed walls produced in factory. Its major advantage is the cost, which is quite low compared to the quality that provides.

- Structural Insulated Panels (SIP): They are sandwich panel used as structure and enclosure for large concrete or steel frame structures. Are made from a great variety of materials, depending on the request of each client.

  When all the panels are ready, they are filled with expandable foam to ensure a tight envelope. This foam helps also for fire, flame and smoke insulation. Often a crane is necessary to set panels, because of their big size.

- Steel panelization: Light-gauge-steel framed walls are usually employed as infill for commercial structures or materials to build interior partition walls. Being manufactured as panels in a factory allows metal panel systems to be quickly erected onsite.

- Curtain walls: Glass façades, sometimes referred as curtain walls, are exterior non-load-bearing translucent enclosures. They are made of glass or aluminum. They can be classified into:
  - Stick systems
  - Unit systems
  - Multilayered glass façade
  - Composite systems

  Some of the disadvantages are the difficulty to adapt these structures to existing buildings and to ensure a proper thermal and water insulation (the possibility to create a thermal bridge is high).

- Cladding Systems: Cladding Systems are non-load-bearing building skins that separate the interior from the exterior, as well as preventing water infiltration, retarding water vapor passage because of condensation, preventing air infiltration and attenuating the sound. It is composed by multiple layers; each one of those performs its own function.

  One of the biggest problems with cladding systems is water leakage: as water moves from the exterior to the interior by forces of gravity or wind-driven rain, rain-screen walls provide a pressure equalization chamber that mitigates differential pressure. With labyrinths, drip grooves and other systems the water infiltration can be resisted.

Some types of cladding panels are:

- Wood cladding: Used in small one-floor or two-floor buildings, but should be applied as rain-screen in projects with greater height due to exposure to the elements. Ventilating the wood cladding allows the moisture in the system to condense. Wood cladding can be detailed to have open joints or reveals.

- Stone, precast and glass fiber reinforced concrete cladding: These systems are designed for wind loading and self-weight primarily. The substructures are made from aluminum or steel. These systems are extremely heavy and not the best option for prefabricated wall panel or modular systems.

- Brick veneers: Prefabricated panel construction allows brick veneers to be placed either as a brick facing in a precast panel and erected as a precast element or to be secured in a steel or aluminum frame, creating a cladding panel for installation.
  Because of greater ease in design, most of them are modular-sized bricks.

5.2.3 Modules

In the spectrum of degree to which prefabrication is finished, modular is the highest, which looks something good for cost at a first time.

Generally, the largest the module is, the more restricted is when speaking about customization. Modular industry is classified by:

Residential	**Industrial**
Temporary	Temporary
Permanent	Permanent

Residential modules can be built with steel or concrete, however it is primarily manufactured in standard wood materials. The commercial modular industry manufactures steel and concrete modular units as entire buildings for onsite delivery. Now we will explain the different modular buildings classified by material:

- Wood Modular: Heavy-duty craning equipment is necessary for assembly in precast, often making this option cost prohibitive for residential and light commercial construction. Wood modules may be used in buildings up to three floors, because over three floors become uneconomical as robust structure is required.

  Modular wood construction progresses in the following sequence:
  1. Floor constructed on factory
  2. Panel walls constructed and sheathed on factory floor and titled onto floor
  3. Roof built and sheathed on factory floor and craned onto walls
  4. Modules are wrapped
  5. Windows are placed
  6. Inclusion of exterior and interior finishes
  7. Transportation of the modules
  8. Placement of the modules on-site.

  Often the units cannot be transported due to the oversized height, weight or length of the module. In addition, sloped roofs may present problems and need to be shipped as a separate element.

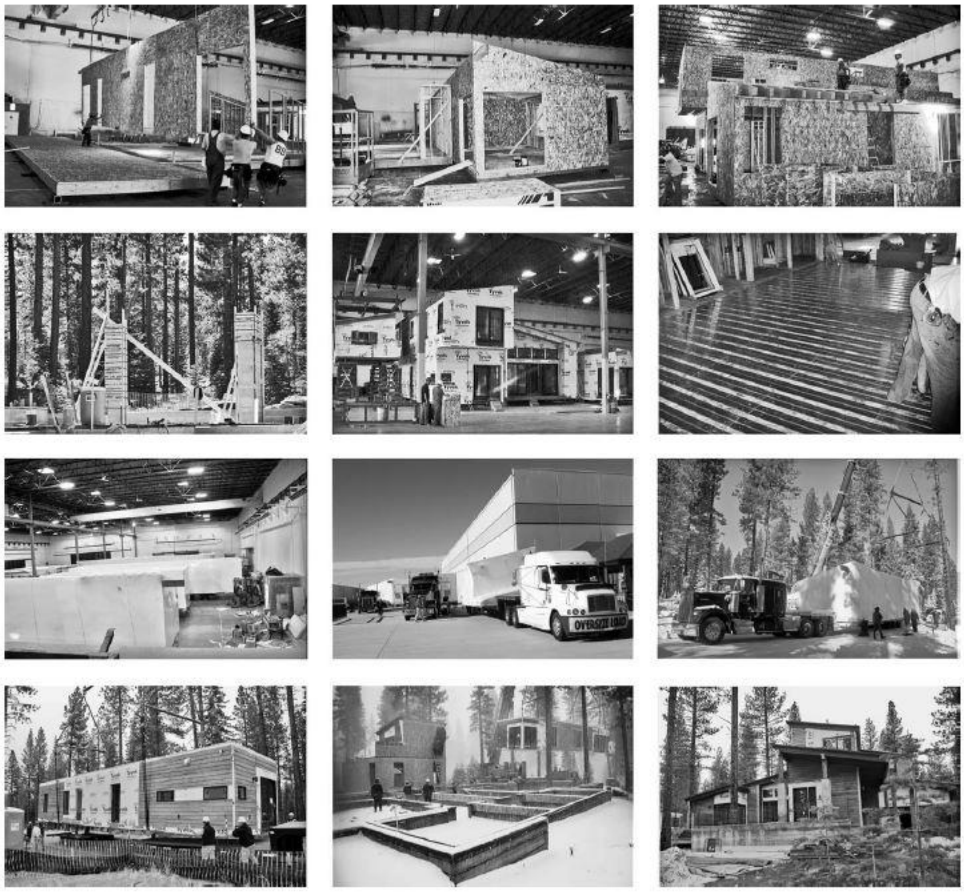


Figure 5: Some examples of modular Wood buildings [7]

- Steel Modular: Steel modular is primarily used in commercial buildings that require more robust structural systems such as taller and higher performing ones. Steel modules have become popular in earthquake-ridden Japan. The structure can be less strong because steel is stronger than wood and does not have to be over-structured for transportation.

  The modules are finished out in the factory with insulation, wiring and ducting in order to complete as much as possible during the building process. An embedded steel frame is used, which can be stacked up to six floors: as a result the entire box modules act as large three-dimensional space frame.

- Modular Bathroom: The biggest problem with onsite building is the time spent involving various trades such as plumbing, electrical installation and tilling. Modular bathrooms can be placed inside a structural frame and used quickly. The critical element is loading, so measures must be taken to ensure that the module does not undergo extreme deflections.

MODULAR DIMENSIONS

Generally, dimensional requirements for modular construction are determined by transportation restrictions. These will be outlined in detail in Chapter 7, however, from the modular builders contributing to this book, rules of thumb have been assembled below:

- Module Width:
  - 13 ft Common Maximum
  - 16 ft Oversized Maximum
- Module Length:
  - 52 ft Common Maximum
  - 60 ft Oversized Maximum
- Module Height:
  - 12 ft Maximum
- Building Height:
  - 1 to 3 Stories Wood Modular
  - 5 to 12 Stories Steel Modular
  - 12 to 20+ Stories Steel and Precast Specialized Modular

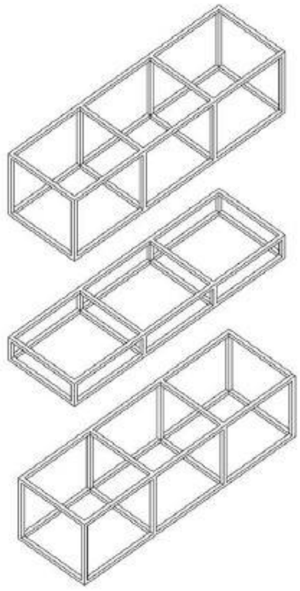


Figure 6: Modular typical dimensions [7]

6. Reasons for choosing a construction system: advantages and disadvantages

At this point, the different techniques for building the inner space, as well as ground and roof with prefab materials will be compared, exposing their main characteristics:

- ***Inner space***

    - Systems for portal frames and frame construction

    They are made of beams and columns of different shapes and sizes that are interconnected to form the building frame. A portal frame is composed of two columns embedded. The frame of a building is composed of several gates placed at equal distance and bearing wall.

    Frame construction is composed of columns that can cover one or more floors and serve as a support for the floor beams on roof. It is not recommended for prefabricated buildings to create embedded links between columns and beams. For buildings of four or more floors, mounting columns in the foundation generally does more to ensure horizontal stability of the building, which requires the presence of rigid cores.

    Generally, frame constructions allow bigger spans and as a result, open spaces without partitions. These constructions are characteristic of gymnasiums, schools, hospitals or factories.

    - Construction by panels

    Constructing by panels implies less open spaces than portal frame construction, that´s the reason why they are mainly used for residential buildings. The panels are made from reinforced concrete.

    Their height depends on the building´s height, and the length varies between 6 and 14 meters. Precast panels are used as interior and exterior walls for buildings, elevator shafts and stairs and they can support loads or just perform as separations.

    There have been some improvements in this technique, such as including only load bearing walls on the perimeter of the building with a floor from one façade to another one. With this technique, we can create open spaces between the exterior walls and configure the interior partitions based in our preferences.

It is really interesting according to the architectural aspect because the quality control is much higher compared to in-situ casting.

- Box frame system

Prefabricated boxes are sometimes used for the building parts such as bathrooms, kitchens or garages. This system allows quick construction and industrialization of the production, as many of the electrical and plumbing systems can be installed at the factory.

Their main problem is the transportation and the lack of flexibility in the management. Just in a few cases can be justified the use of box frame system, such as with large boxes productions, in which money and time savings will be huge, as all the equipment is included in the box.

In comparison with prefabricated walls, the cast in situ system allows a higher freedom for the dimensions and shapes. Prefabrication is indicated for buildings that imply the repetitions of same elements but it´s much more interesting to cast in-situ circular walls.

- ***Floor and roof constructions***

There is a wide range of elements and floor systems. Prefabricated floors are regularly used in all kind of buildings, as they are one of the oldest building products. There are some kinds of floor and roof systems:

- Hollow-core slabs

The hollow core slabs are reinforced concrete slabs, which can be supplemented by the addition of a compression slab, allowing the implementation of keying joints between the slabs. They are used in buildings with large spans and medium loads (hospitals, schools, shopping centers, industrial buildings).

Slabs present many advantages from an architectural point of view, such as liberation of built space offering many layout possibilities by removing intermediate bearing supports.

- Ribbed slabs

They are TT or reversed U sections made with pre-stressed concrete, suitable for large spans and heavy loads (industrial buildings, storage areas, distribution centers)

- Metal floor deck and pre-slab floor

These floors are used for small spans and moderate loads, such as homes, apartment buildings or hotels. Contrary to hollow-core slabs, these ones need the use of shoring tower in the middle of the floor. This floor is light and cheap, but needs the installation of fire protection systems and a false ceiling.

- Floor with girder slab

Also called resistant formwork, are topped with a slab of concrete, and mainly used for small lengths and reduced loads, what allows not use any crane. It´s interesting in places where it´s not possible to access with the crane. The obvious disadvantages are the reduced span and the need for false ceiling or coating.

- Floor cast in-situ system

As in the wall, it allow to get much more freedom. It can´t support large spans but the finishing is much better than pre-cast systems because there are no joints.

- ***Façade system***

The possibility of choosing between different textures and colors in prefabricated façades is especially interesting for buildings with architectural importance.

As we said before, precast elements in factory allow getting high finishing quality thanks to permanent control. Regularity of materials and the uniformity of the conditions allow using precast concrete in such an important element as the façade.

These prefabricated elements are poured horizontally like a slab which enables to get a big variety of shapes, which is not the case for cast in situ walls and their rectangular shapes. The design of the formwork can be modular, allowing us to add or remove portions of elements, to create a shape slightly different.

Build with precast elements presents another advantage when we want to substitute or expand the building, because removing the terminal elements can be done very quickly and presents no inconvenient.

CONCEPTUAL AND THEORETICAL DEFINITIONS OF BUILDING CONCEPTS

1. Objective

The purpose of this part is to understand the conceptual meaning of the different concepts used in industrialized processes. First of all, it is important noticing the conceptual difference of modules and building blocks as these concepts will be closely related with the explained below.

General explanation of industrialization leads to standardization, modularity and modularization. Prefabrication is the next step after industrialization, since it is inconceivable prefabrication without industrialization. After prefabricated elements are built, pre-assembly takes part in the building process. Modularity and modularization concepts are also explored, because they are closely related to standardization.

Finally, the complete building system is finished through the transportation of the pre-assembled prefab elements to the building site and the final assembly of them.

2. Module and building block

A *module* is an essential and self-contained functional unit relative to the product of which it is part [1]. In an industrial context, it is important that this functionality has to be sufficient for independent testing.

The module has, relative to a system definition, standardized interfaces and interactions that allow composition of products by combination. We cannot find the modularity, if we do not know the system to which the module belongs.

They must have also the demand for interchangeability. Modules can only be interchanged if they have compatible interfaces and interactions, and the compatibility is ensured by setting a common system standard for interfaces.

So defining a module requires three characteristics:

- Being interchangeable: There must be possible interchanging the module between systems.
- Must possess essential and self-contained functionality *relative to the product of which it is part*: even if the module takes part of a much bigger system, it must be able to perform functions by itself.
- Must be able to interact and perform with other modules.

As a result, a module has to take part in a much bigger modular system, since this is necessary to define the module itself.

A possible example of a module is a wall panel, because of these reasons:

- It is possible to change a wall panel for another one in case of being broken.
- The wall itself can be tested whether it is placed on its final position or not. Besides, it possesses its own function: isolating from the outside.
- It interacts with other modules, as it needs to be joined to the floor and the side walls.

The meaning of *building block* is completely opposite to module´s meaning. A building block is reduced to a more limited functionality compared to the final product, as **it does not possess any substantial functionality** compared to the construction of which it is a part.

A good example for building block is a brick: by itself it does not have any self-contained functionality and must be put together with another bricks to form a wall, and then it will perform as a module.

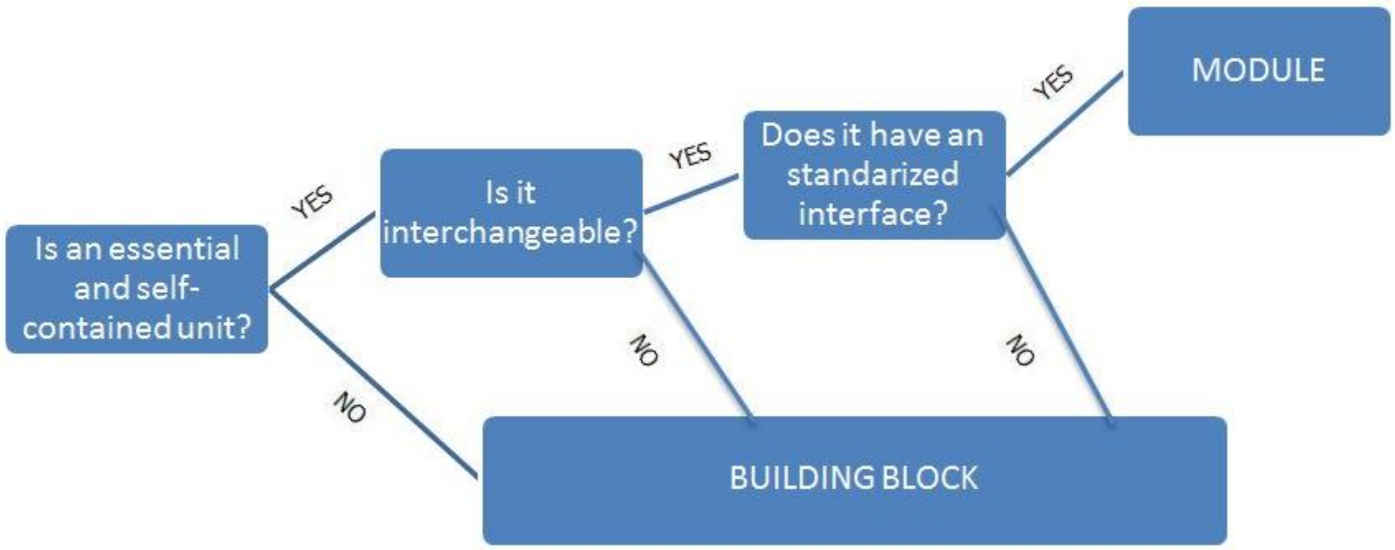


Figure 1: Decision Support Methodology for Module and Building Block

3. Industrialization

***Industrialization* is a socio-economic process through which a society will change from pre-industrialization into industrialization** (Abdullah et Al., 2009)**, and is part of wide modernization process through development of new technological and production methods.**

In industrialization, manual labor processes are replaced by mass production and craftsmen, as well as assembly lines. It involves investment in equipment, facilities and technology.

Perhaps in building industrialization a complete product is not a standard building, because necessities of end users and relevant sites are completely different in each case.

In construction, industrialization means for eliminating or reducing on-site activities by constructing element in specialized facilities and transporting them to construction site. Two main principles aiming for *industrialization* are found in the construction literature: <u>lean construction and buildability/constructability</u>.

Lean construction is a methodology aiming at streamlining the whole construction process while product requirements are realized during all the phases (Anders Bjönfot and Lars Stehn; 2005). The main goal is the elimination of waste.

Buildability/constructability is a process and product based principle. In contrary to modularity, **buildability/constructability is more a goal than a means for product and process efficiency** (Anders Bjönfot and Lars Stehn; 2005) [8]. An interesting connection is the relation between buildability and manufacturability, design for assembly (DFA) and design for manufacturing (DFM) methodologies.

DFA is a process by which products are designed with ease of assembly in mind. Some of the measures to achieve it are designing fewer parts and including some features which make them easier to assemble.

On the other side, DFM is the engineering art of designing products in such a way that they are easy to manufacture, and it focuses on the design aspect and producibility.

Both are methodologies aim at reduced complexity in assembly and reduced assembly costs, therefore their relation to modularity is strong.

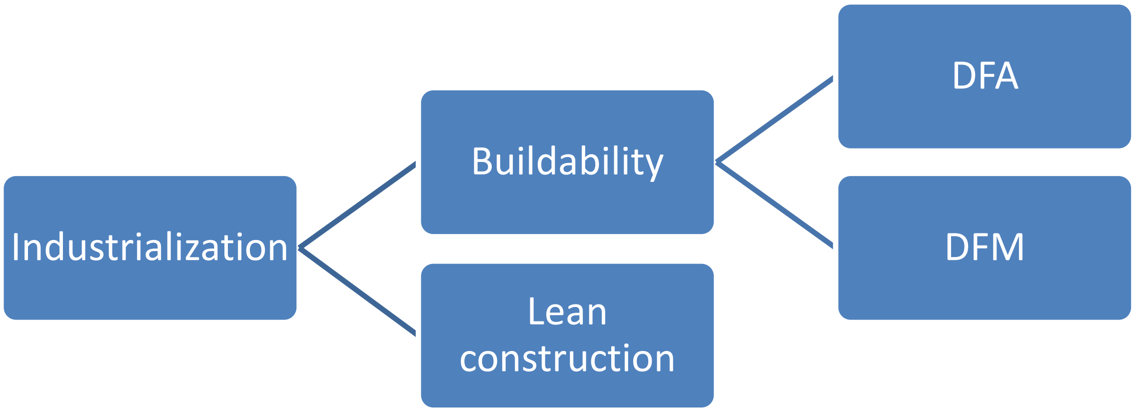


Figure 2: Industrialization-related concepts

4. Prefabrication

Prefabrication is the manufacture of parts of the final structure on a site different to its definitive location. This labor can be done in a specialized factory, or next to the work, but never on-site. Pre-assembly and modularization are then extensions of the concept of prefabrication. **These three concepts differ on the degree of completion of the pieces and the amount of on-site labor required installing them.**

Building with prefabricated systems encompasses the production and use of pre-planned components or modules as a solution to build with more efficiency.

Prefabrication has applications in building projects, where beams, columns and walls can be found, as well as small building elements.

As a result, prefabrication can be performed considering later pre-assembly or not, and depending on the degree of completion.

5. Standardization: Modularity and Modularization

Standardization is the organization and completion of a substantial proportion of final work through regularity and repetition, before installing the elements in its final position [3] [6]. As a result, it is closely related with prefabrication and pre-assembly.

It also works by ensuring accurate fit and interchangeability of components, specially ensuring the compatibility between the different interfaces of the elements.

Anyone could ask himself why modularity and modularization is included in standardization. The reason is because of interchangeability. As designing standard allows interchanging modules, it involves designing based on modularity.

Prefabrication cannot be either conceived without modularity and standardization, so all these concepts are closely related and they depend on the previous ones.

- Based on "*Standardization and Pre-assembly; distinguishing myth from reality using case study research"* (GIBB, 2001) and [6], Modularity is an attribute which relates to the structure of the system which permits the interchangeability and variety of the different modules, not only one.

  As it is necessary interchangeability, modules will need compatible interfaces and interactions.

  It must be understood in relation to both the structure of the system to which the module belongs, and in relation to the amount of functionality of the module relative to the product of which it is part.

  For creating modularity it is really necessary to use modules with the specific characteristics named above. Through the combination of different modules, modularity can achieve products.

- According to *Standardization and Pre-assembly; distinguishing myth from reality using case study research"* (GIBB, 2001), Modularization is the activity in which the structuring in modules takes place. If we are thinking about designing a house, the process of dividing the different main parts into modules, that is modularization.

6. Pre-assembly

Pre-assembly means to “assemble-before” and is a process by which various materials, prefabricated components or other equipment **are joined together at a remote location for subsequent installation as a unit.** Preassembly may be completed at the job site in a location different to the place of installation.

Pre-assembly is generally considered to be a combination of prefabrication and modularization, but it is not always correct, as pre-assembly can exist without modularization.

Some people have an incomplete picture of what pre-assembly means, because they often equate pre-assembly with full modular building techniques. According to “*Standardization and pre-assembly; distinguishing myth from reality using case study research*” (GIBB, 2001), four types of pre-assembled elements can be defined:

- *Component manufacture and sub-assembly*: This category includes all small-scale sub-assemblies that would never be considered for on-site assembly, as well as other sub-assemblies like door furniture or light fittings. These elements are manufactured offsite but do not form part of the main structure. Bricks or tiles are considered building blocks, but sub-assembly components can be modules.

- *Non-volumetric pre-assembly*: These items are assembled in a factory prior to being placed in their final position. They are composed of many sub-assemblies and constitute a significant part of the building structure.

Some examples are wall panels and structural sections.

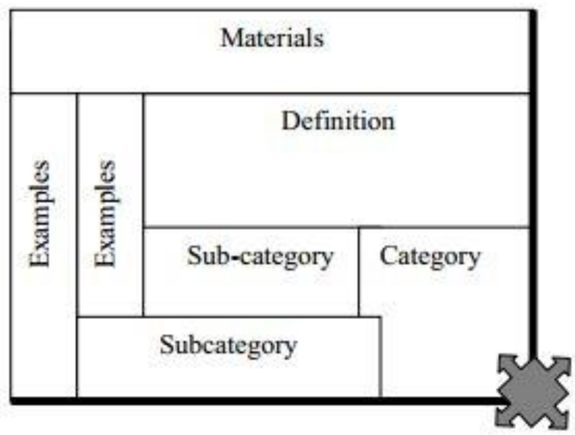


Figure 3: Explicative chart for Figure 4 [6]

In this figure (*Re-engineering through pre-assembly: client expectations and drivers;* Gibb & Isack; 2001) it is showed more clearly the types of pre-assembled elements:

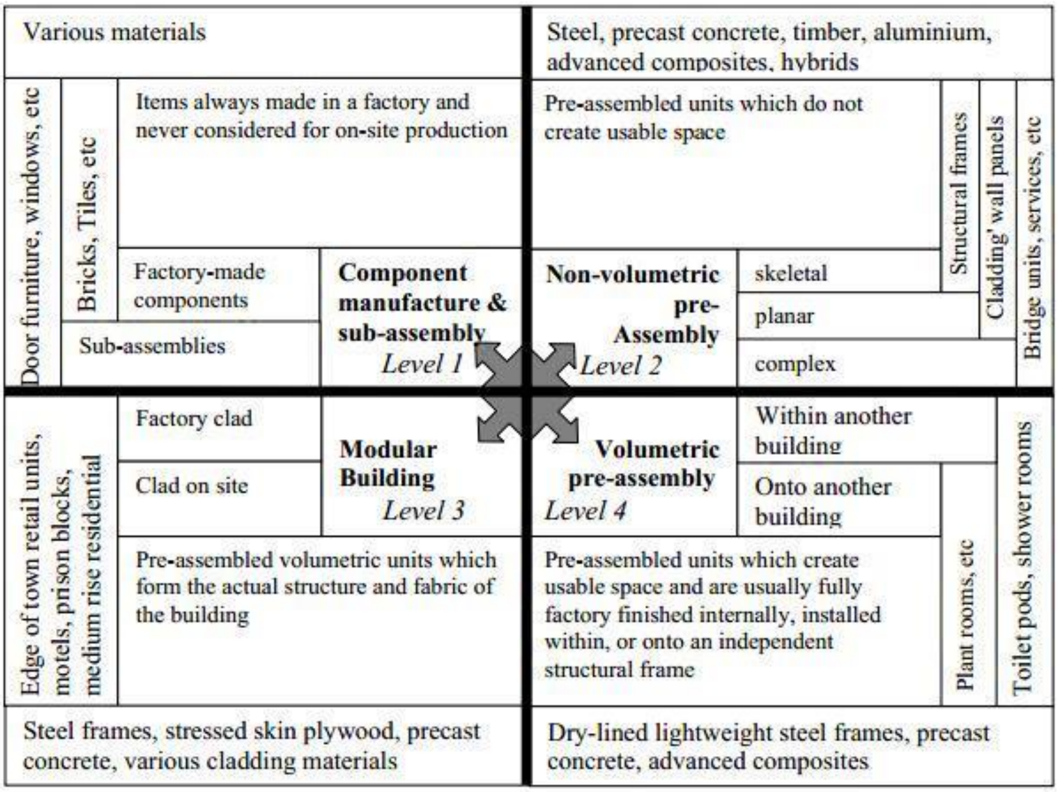


Figure 4: Categories in pre-assembled elements [6]

- *Modular Building*: In this case, the units form the building, as well as enclosing the space. Some examples are office blocks and modular units made of concrete with more than one floor. This is the finest example of module as the unit itself has self-contained functionality but it is mandatory being standard.

- *Volumetric pre-assembly*: These elements are like non-volumetric pre-assembly elements put together; the main difference is that they enclose space.

  Some examples are plant room units, pre-assembled building services or lift shafts. As the previous case, these can be considered as modules in case they are standardized.

To clarify if pre-assembled elements are modules or building blocks, we should see if they are standard or not, because we can find both possibilities in the category.

Except for "Component manufacture and sub-assembly", which can have or not self-contained functionality, **the other components satisfy always this requirement for being modules**. As standardization involves interchangeability and this is necessary for defining components as modules, it is mandatory for all pre-assembled component being standardized in order to perform as a module.

In the case of "Component manufacture and sub-assembly", only sub-assembled and standardized components have self-contained functionality, and are modules.

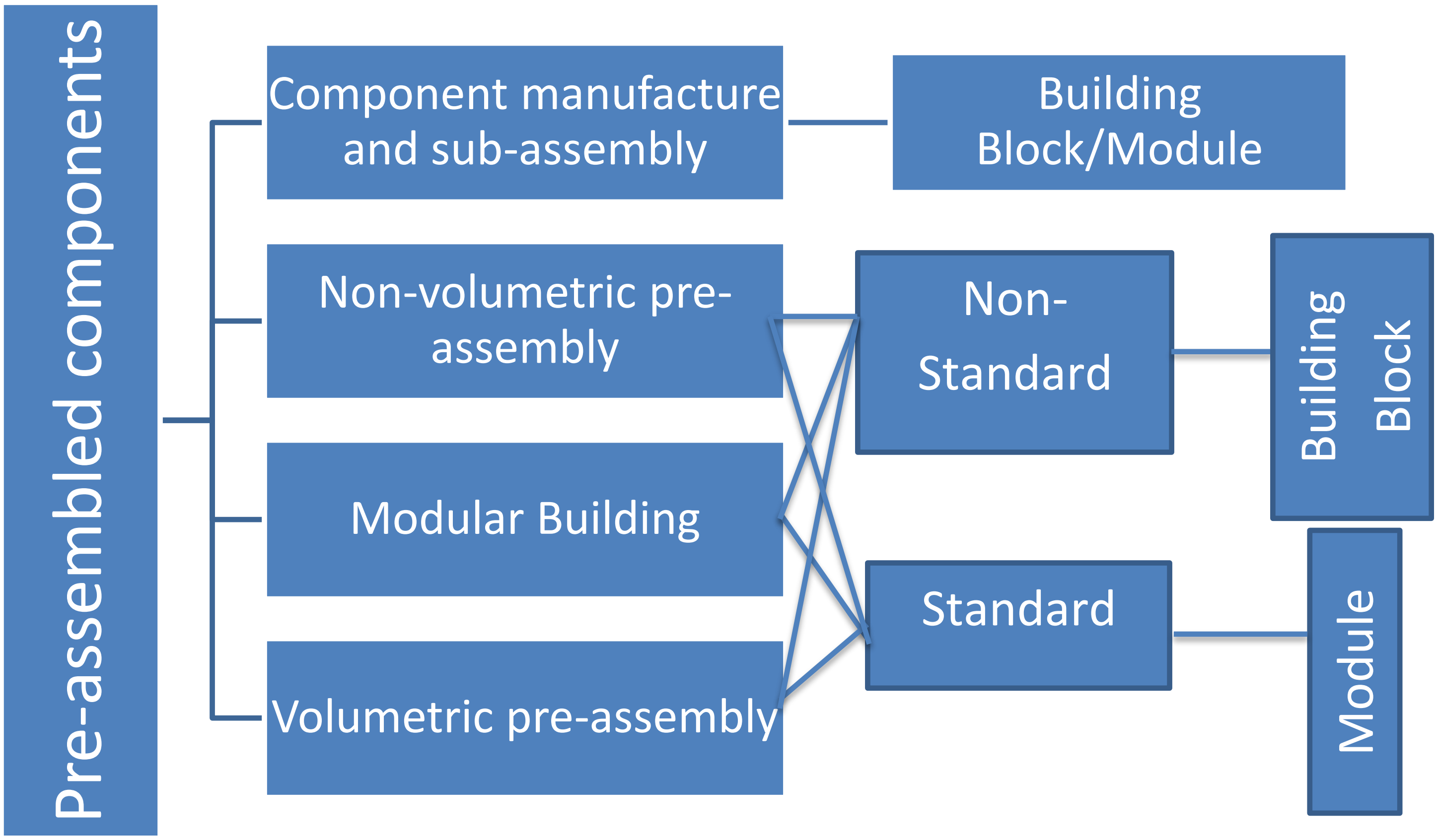


Figure 5: How can pre-assembled components be considered as modules?

7. Different approaches for industrializing components

The figure below shows how industrialized components can be classified, depending on their intrinsic characteristics.

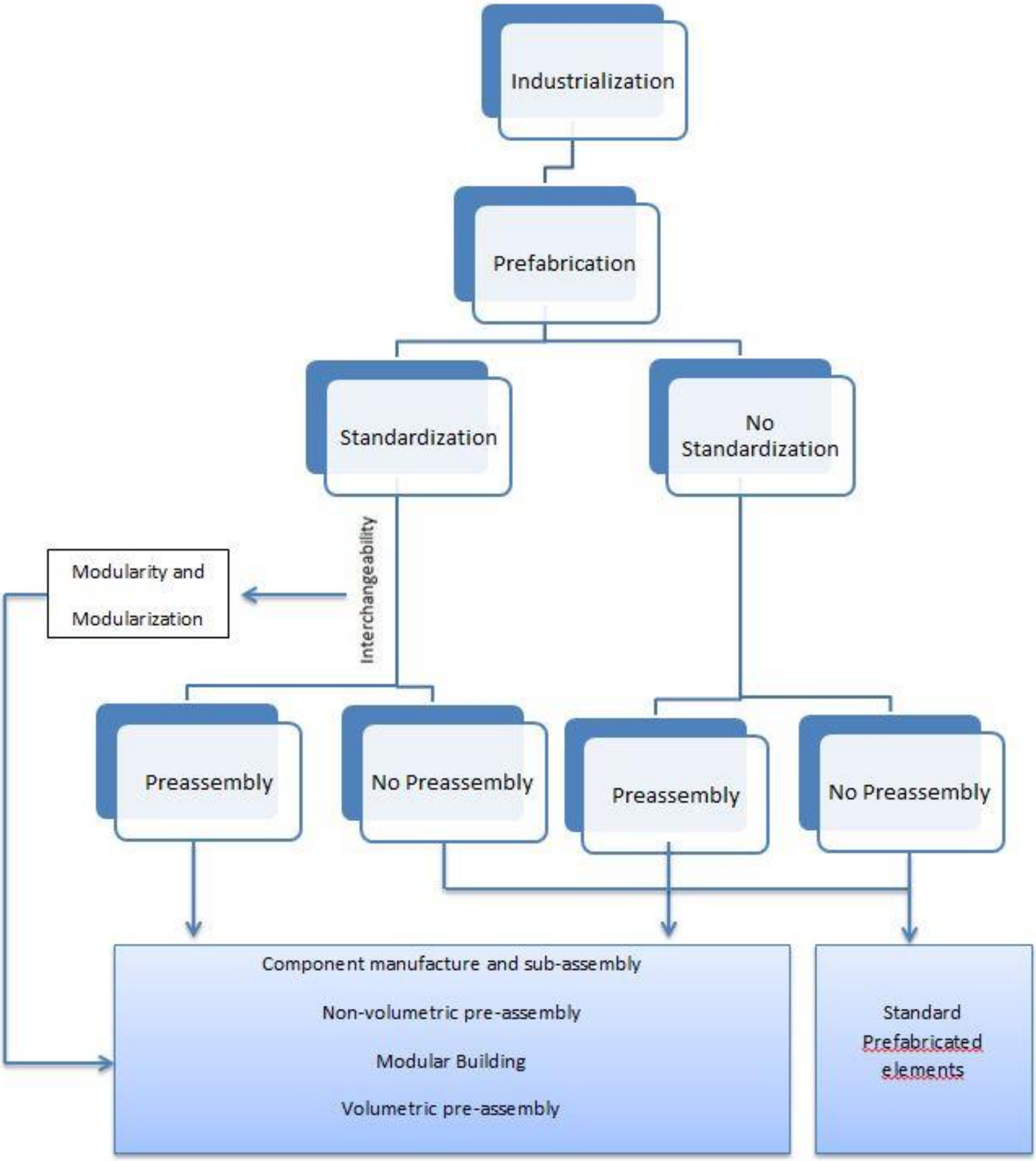


Figure 6: From Industrialization to Preassembly

Prefabrication cannot be conceived without industrialization, since prefabrication is an industrial process, which is possible due to industrial development in our society.

But prefabrication does not involve a component being standard:

- Prefab non-standard elements can be built if small quantity is required. Obviously, building costs are much higher, and it is not always profitable.

- Prefab standard elements are the most typical ones, as they can be used for multiple cases and purposes. Building standard involves interchangeability, and this can only be achieved by modularity and modularization, as we explained before.

Regardless components are standard or not, they can be pre-assembled before being placed in its final place. Decision of building pre-assembled components depends on the degree of completion we want to achieve at the onsite location.

Pre-assembled standard or not elements can be classified in four different categories (component manufacture and sub-assembly; non-volumetric pre-assembly; modular building; volumetric pre-assembly) depending on its characteristics: if they enclose a volume, if they are just small components…and on the degree of completion.

One may think that these elements have no difference whether they are standardized or not, but it´s not correct: as we said before, standardized components require much less work in the final place and they are “ready to use”. Obviously standardization makes a great difference: considering an object a module or a building block.

Finally, not pre-assembled elements, regardless they are standard or not, lead to “standard prefabricated elements”. As the previous case, the difference lies on the work the components need when they are taken to the final place.

As a conclusion, what is obvious is the complexity of the terminologies and the difficulty to define specifically a component in its category, but the definitions given above will help hugely to classify each component in its category.

8. Building system

A building system includes the industrialized process by which components of a building are conceived, planned, fabricated, transported and erected on site (Junid, 1986). The system includes a balanced combination between the software (system design) and the hardware components.

It is defined as **a standardized element designed to be added or used as part of an arrangement of building modules to form a connected whole**. As it is conceived to be used with other elements, it **must be modular**.

Building systems are used to simplify complex planning and constructional processes: they are not related with a specific task, but can be applied as universal solutions. Building system is often referred to as prefabricated systems because of the industrial nature of construction production. [5]

The subcategory of prefabrication includes all systemized off-site manufacturing of components and elements. Prefabrication allows a cumulative development of technical knowledge: connections, details and technical standards.

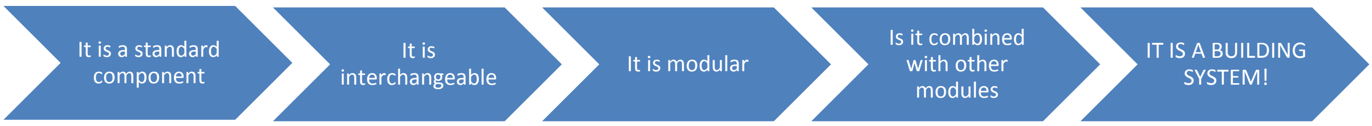


Figure 7: Considerations for defining a building system

9. Some clarifying questions

1. *Does prefabrication lead to modules?*
   No, prefabrication does not mean *modularity* or *interchangeability*. A prefab element can also be considered a *building block*.
   Prefabrication just involves manufacturing elements at a different jobsite.

2. *Can pre-assembled elements be considered as modules?*
   No, all pre-assembled elements may, or not, meet modules' requirements: being interchangeable, having self-contained functionality and interacting with other modules.
   These requirements can only be achieved through standardization.

3. *Can standard elements be considered as modules?*
   No. Not all standard elements do have self-contained functionality. Only those ones designed according to pre-assembly principles.

4. *Which is the most logic way for designing components?*
   Obviously, all components should be designed by combining prefabrication, standardization and pre-assembly. Thus, lots of work will be saved and the only task for the work is joining the different elements.

5. *What leads considering a prefab element a building system?*
   Simple:
   - First of all <u>being a module</u>: the elements must meet all the required characteristics.
   - Second: combining the different modules.

In the picture below, it is showed more clearly which category corresponds to each element:

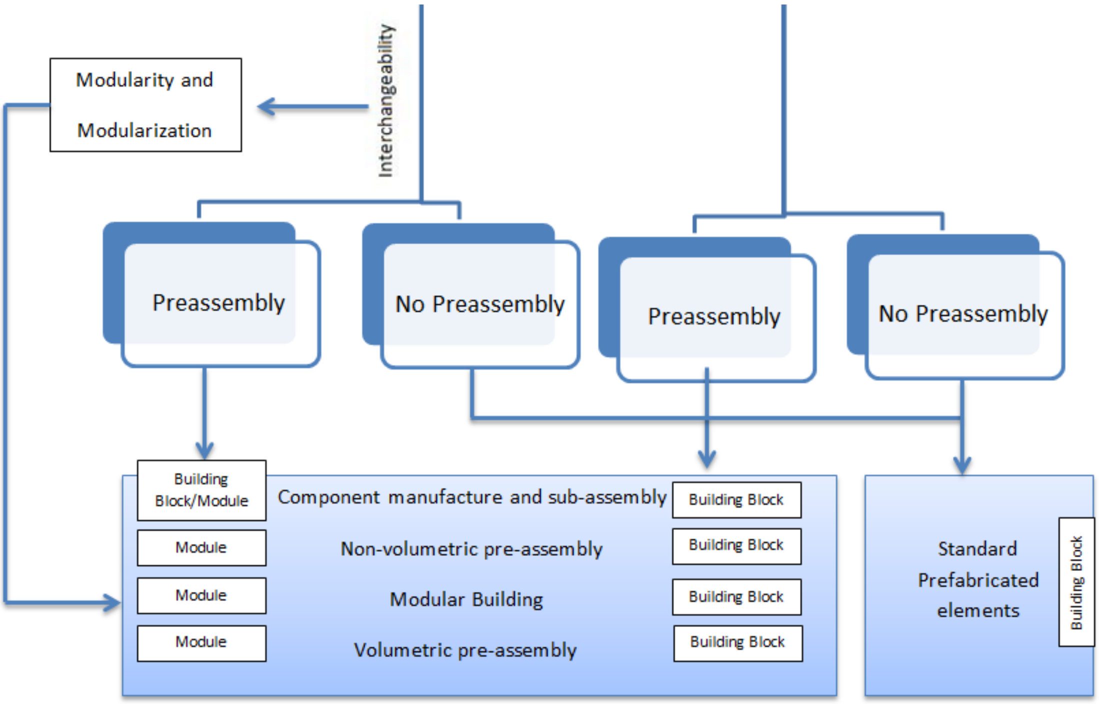


Figure 8: Explanatory picture for determining if an element is a module or a building block

6. *How does each standardized pre-assembled component correspond to previously seen prefabricated materials?*

In previous chapters, pre-fabricated materials were classified into 3 major groups, depending on the degree of finish. These three groups are: Components, Panels and Modules.

Based on my personal appreciation, the classification is:

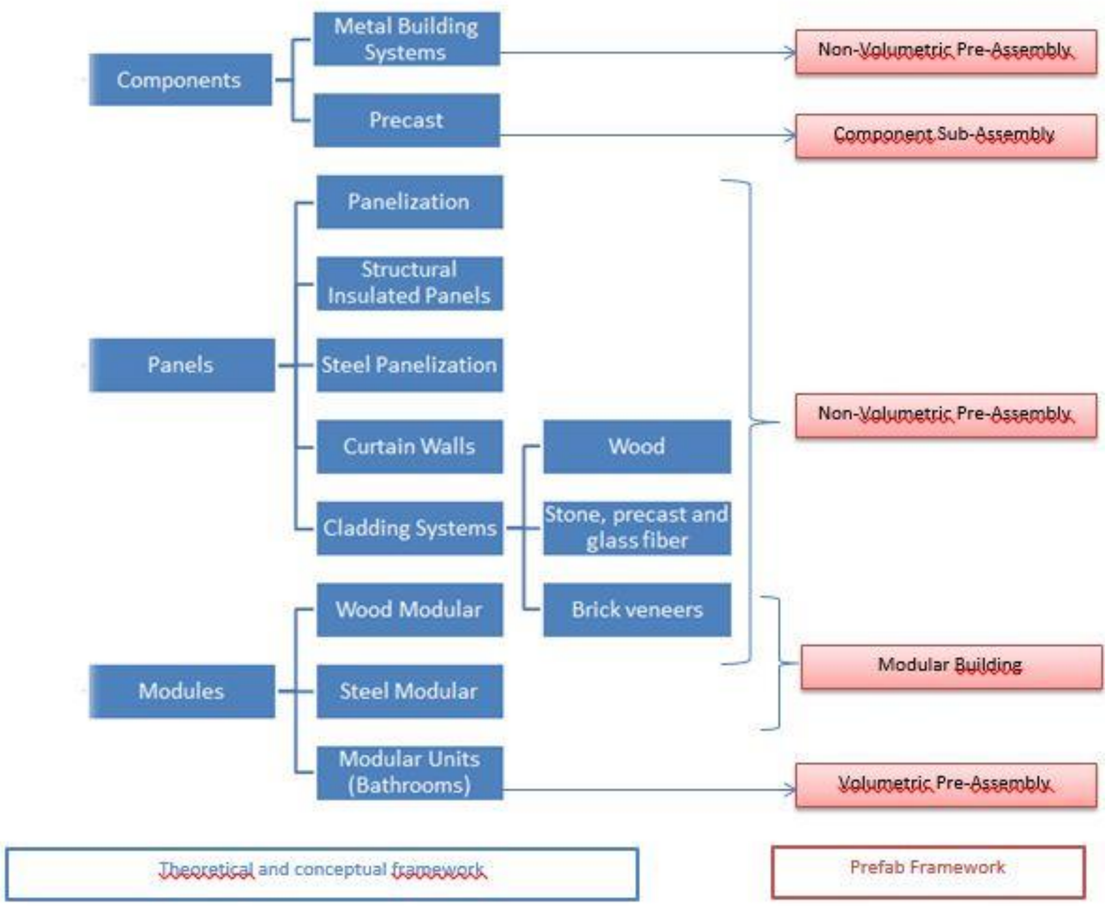


Figure 9: Correspondence of Pre-Assembled modular components and prefabricated elements

BIM ENVIRONMENT

1. What is BIM?

We tend to think that 3D designing programs are used only in the first steps of the development of the product, but not with BIM. It is difficult finding a universal definition for BIM, but we can say that is an information base which can be used throughout the life cycle of the building, including servicing, construction and recycling. It is not a technology; it is a process which applies to all aspects of the construction of the building. [14]

BIM includes **geometrical information** (we can both use 3D or 2D models), **non-graphical information** (which helps to clarify how must be used) and **linked information** (project details).

It also helps to determine incompatibilities during the design stage, prior to construction, since the elements are interrelated to each other. It is important understanding that objects are not isolated entities in the virtual environment, and how they are linked is vitally important.

BIM is based on the *Parametric Modelling Principle*: altering the width of a wall will have an impact in the whole structure, since loads will not be the same. Because of that, objects in BIM know which is their purpose and why are they placed there. But also non-parametric and semi-parametric object can be used within BIM framework, although they do not take advantage of full BIM potential.

Another benefit is that having BIM during the early stages of the process allows testing various components and then finally choosing which one is best, depending on what we look for in our project.

As a result, we can state that BIM has 6 Dimensions: 3 Geometrical Dimensions, scheduling, cost and life cycle.

Therefore, with the integration of 3D modelling, the 4D (3D+scheduling) is feasible and helpful for the industry, especially if using JIT (Just in Time). Tasks are completed simultaneously, not sequentially.

Cost is the 5th dimension of BIM, as the components have cost information associated with them. Life cycle analysis is the last of the dimensions and focuses on the forward thinking ways to design construct and manage modular buildings.

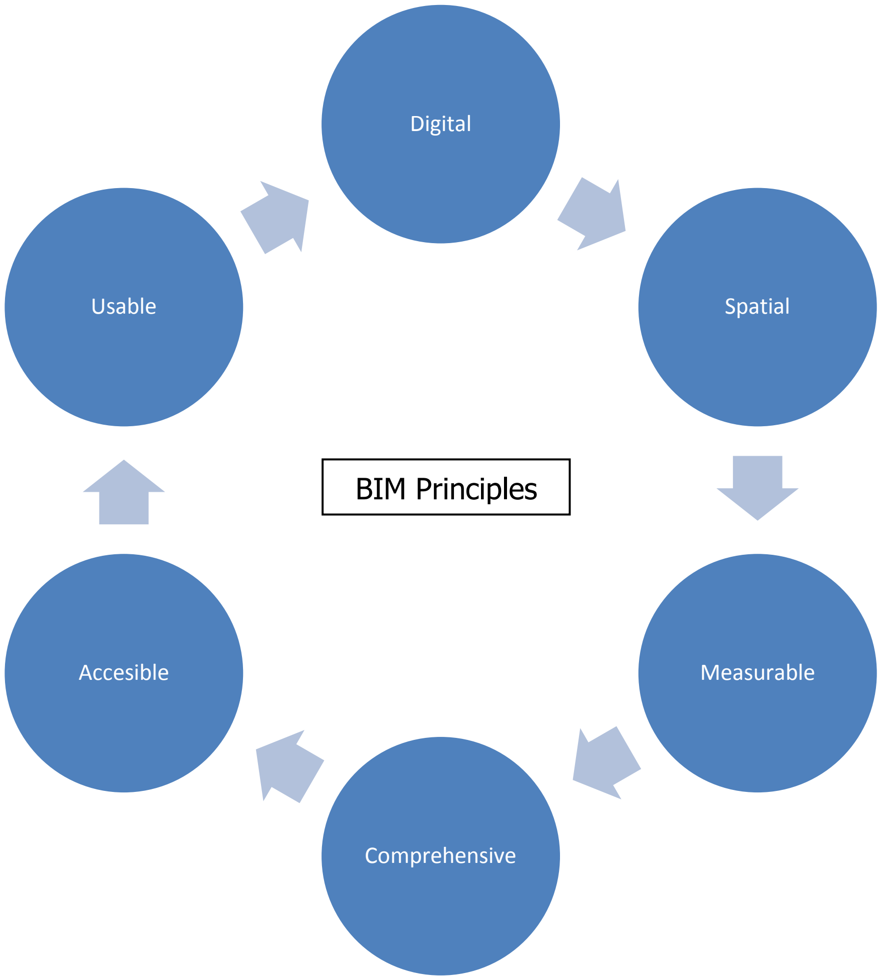


Figure 7: BIM Principles

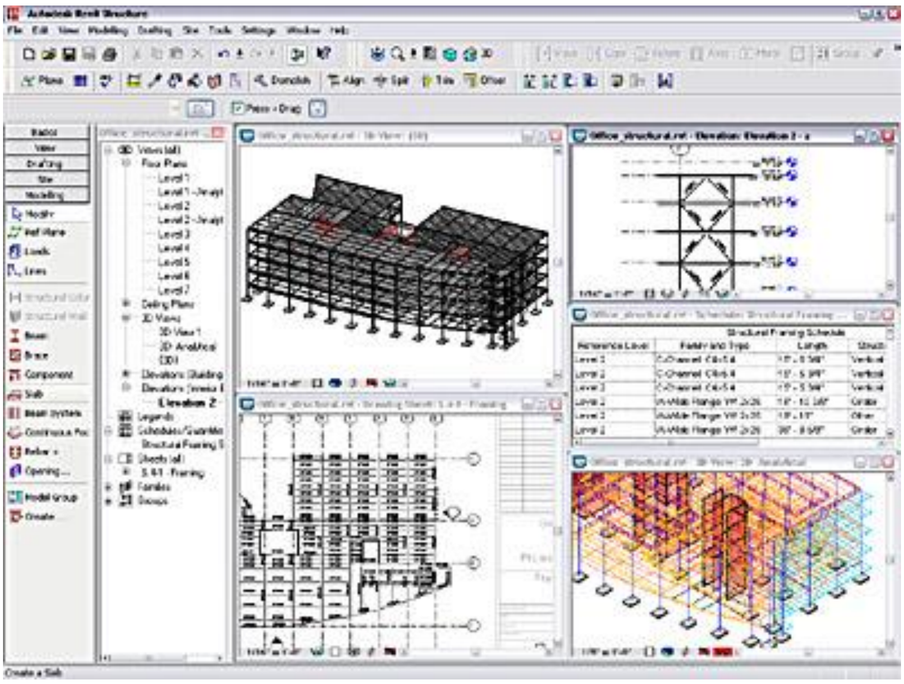


Figure 8: Designing with BIM software (REVIT SOFTWARE)

2. What is not BIM technology?

The definition of what constitutes BIM is subject to variation and confusion, but we will describe modelling solutions that do not utilize BIM design technology [14]:

- Models that contain 3D data and not object attributes, like for example *Google SketchUp.*
- Models with no support of behavior: These models define objects which cannot be adjusted in their positioning or proportions because they do not use parametric intelligence.
- Models composed of multiple 2D CAD reference files which must be combined to define the building.
- Models that allow changes to dimensions, but these changes are not reflected in the rest of the components.

But it is also important to say that <u>there is not a strict delimitation of what is and what is not BIM</u>, and <u>some non-parametric objects can also be used in BIM</u> environment if its use is not extensive

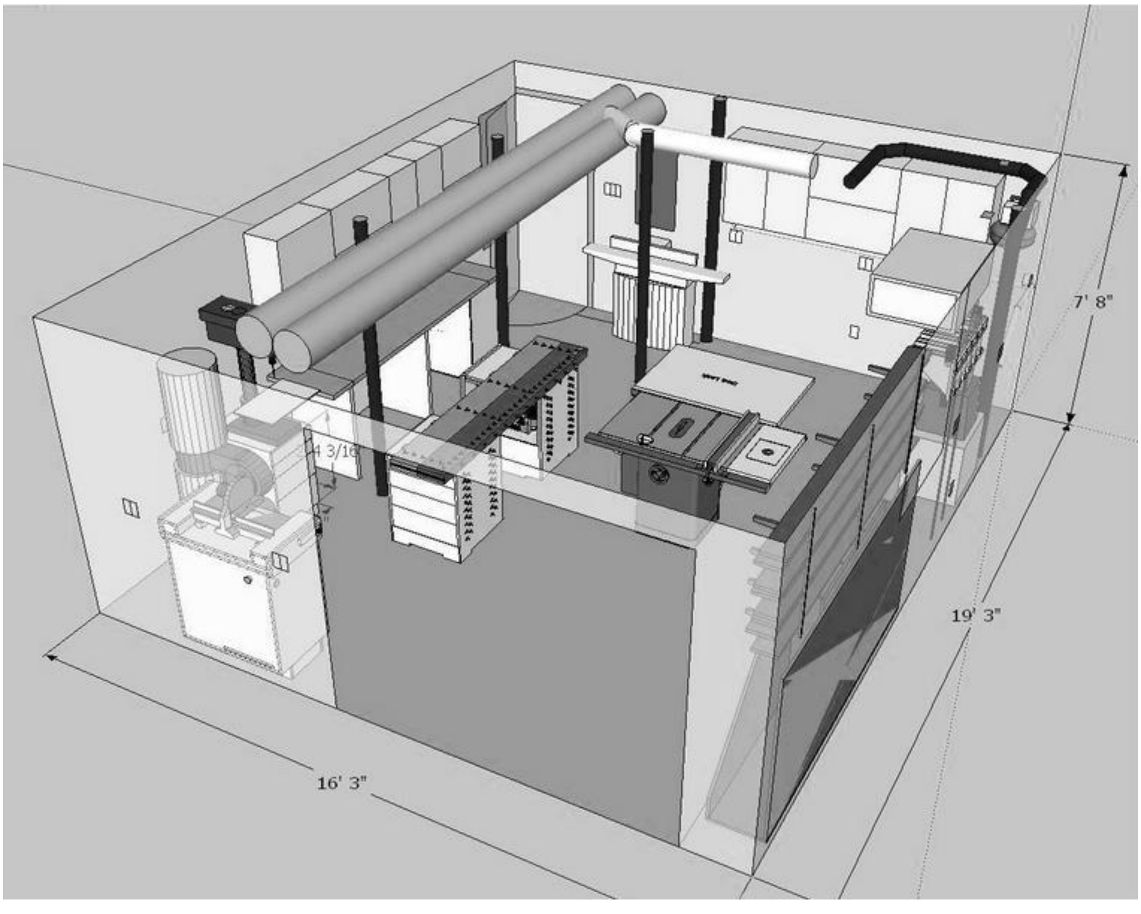


Figure 9: Sketch-Up Example (REVIT SOFTWARE)

3. Parametric and non-Parametric Modelling

3.1 What is parametric modelling?

At a first time, original CAD engines used coordinate-based geometry to create graphic entities. From that point, the engine evolved to standalone 2D drawings, which finally represented a design element.

The software made the models smarter and easier to modify by adding more intelligence to the elements, leading to much more complex components. But at the end, the elements continued being coordinate-based, and the difficulty to edit them was inherent to the system.

As a result, the parametric model uses numbers or characteristics to determine the behavior of the graphical entity and to determine the relationships between the models. The dimensions drive the geometry, as opposed the geometry driving the dimensions (what happens in traditional 2D and 3D models). [22]

When you change a dimension value, this causes the model size to change, and the relations/constraints used to create the models are also captured.

The advantages of the parametric model are obvious:

- 3D solid models offer unlimited range of ways to view the model, not only orthographic views.
- 3D modelling software can update related parts of the model when design changes are made and there is an association between parts.
- Changes can be made both at a very detailed level and at structural level.
- Modelling errors are highlighted for the user, something that is not possible in conventional 2D systems.
- 3D models capture much better the design intent, which helps to understand how the model will behave when design changes are made.

Since this is a BIM-related project, it will focus mainly in BIM parametric software and characteristics, but not in other parametric modelling tools for considering them irrelevant.

3.2 Non-Parametric Modelling

Static, nonparametric objects are simple components that cannot be modified. The functionality of those components is much reduced, as they only represent the object, without any other finality. Most of decorative components, such as furniture, light fixtures and fixed shape elements are generally non-parametric.

For example, when a manufacturer has only one type of lamp, without any possibility of changing the color or the size, it is no worth designing a parametric model of that lamp.

It is also important considering semi-parametric models: those which do not have dimensional parameters but do contain informational attributes. In this case, the solid graphics are not modifiable, but the finishes are. Some examples of semi-parametric models are light fixtures.

Obviously, they have a limitation on what they are capable of and what can they offer to the building model and can be considered a “light” version of BIM models.

Their main characteristics are:

- Is dependent on the geometry of a form
- Rules and constraints are not as influential
- Small-sized and easy to create
- If we want to make a component as a non-parametric object, this component will be very difficult to manage, owing to the amount of components and variations possible.
- Null exploitation of building information modelling capabilities, remaining the sensation of being in computer-aided design stage

It is obvious to conclude that non-parametric modelling objects use is only considered as the entry level of BIM design, like a necessary step for moving from CAD to BIM. For that reason, non-parametric and semi-parametric objects should only be considered as transition ones.

Since this technique does not exploit the full potential of BIM, it is highly recommended stop using them progressively.

4. Which are the benefits of BIM?

- Preconstruction benefits:
    - Feasibility of the project is clear from the first moment
    - Increased Building Performance and Quality
    - Improved collaboration between different actors involved

- Design Benefits:
    - Earlier and more accurate visualizations of a design
    - Corrections are automatically made, since used elements are parametric are employed
    - Generation of consistent drawings from early stages of the project
    - Calculation of costs during the design stage
    - Improvement of energy efficiency and sustainability

- Construction and fabrication benefits
    - Use of design model as basis for fabricated components: If the design model is transferred to a BIM fabrication tool, it will contain an accurate representation of the building objects for fabrication and construction.
    - Quick reaction to design changes
    - Synchronization of design and construction planning
    - Better implementation of lean construction techniques

- Post construction benefits
    - Better management and operation of facilities
    - Integration with facility operation and management systems

5. Why prefabrication+BIM?

By having all the prefabricators' information in the BIM model from the beginning of the building cycle there will be a reduction in costs and errors, improving efficiency.

Prefabrication makes objects easier to produce and assemble; it can be done in less time, so it is less expensive. As a result of the simplicity, the number of errors is reduced as the quality improves.

If we are using prefabrication combined with BIM, it is especially important that prefabricators take part of the designing process from the first stages of the project. If we do so, the saved time will be huge. When prefabricators are not involved in the process from the first stages (where architects' decisions are taken), some information will not be accessible for them, creating inefficiencies.

But at this moment it is a common practice not giving the proper consideration to the activities involved in the next phases. To solve this problem, prefabricators should include all the digital information of their products during the early stages.

And it is here where most work should be done, making possible the availability of prefabricated components in digital format, so they could be used in the design, the offsite construction and the maintenance stage.

By having the manufacturers' digital models of the components included in permanent libraries, the time saved increases hugely. For that purpose, BIM has a core database which helps to coordinate between the different agents involved in the process: designers, architects, suppliers and engineers.

BIM includes all the geometric information about the different parts of the building, but it also allows introducing ones such as cost, thermal values, resistance or acoustics. That is the interesting feature of BIM, because it can be used by many sectors involved in the development.

We can say that the most effective use of BIM models was for design coordination and walk-through animation. The greatest challenge of using BIM in construction projects is the implementation of the process itself, because development of BIM process requires huge knowledge of construction methods and processes.

6. CAD vs. BIM

Now we will try to make an approach of all the concepts seen before but in a virtual environment. First of all, it is important to explain how virtual objects are considered both in CAD and BIM software.

CAD stands for Computer Assisted Design, and is a set of 2D and 3D tools based on points, lines and polygons. The combination of these tools allows creating 3D models, but they are not much more intelligent than 2D line work.

Most important, these elements do interact each, but do not have a real entailment. For example, drafters drew four independent lines to represent the edges of a wall. Generally speaking, those programs which contain 3D objects but do not have the ability to contain attributes are NOT considered BIM programs.

In the late 1980’s, a completely new kind of design software was developed, which uses 3D models to mimic the real-world structures, such as walls, floors or beams. This software is called Building Information Modelling (BIM). First of all, it is important to create an informatics model of the building to collect all the information required.

Once the object is parameterized (all the important information is included in the object itself), the relationship between the different components in the building can also be controlled. As walls know that they are upright, connecting them to other walls, having floors above and below them and making opening is much easier. They also contain information, such as the materials they are made of or whether they are interior or exterior.

7. Modules or building blocks

The logic approach we have to make now is to decide whether the virtual objects designed can be considered modules or building blocks. According to the definitions seen before, a building block must have a self-contained functionality.

In CAD design, the different components are composed by the combination of lines, but although they do represent an object, it is not conscious of being an object. They cannot either interact with other components or being interchanged, as they cannot be considered as objects. As a result, CAD components are defined as building blocks and there is no chance for considering them modules.

On the other side, it is obvious that many objects created with BIM software must be considered modules. If we look at a beam, which is a typical example of component designed with BIM, it is obvious that it has self-contained functionality.

Moreover, since it is designed with BIM, it contains all the relevant information of the relationship of the object with the rest of the structure. But, can we consider any BIM created element a module? Obviously yes: BIM does entail that the component is interchangeable and that it has a standardized interface.

Otherwise, BIM would not be considered what it is if modules were not employed (it is important remembering that objects in BIM perceive its purpose, so they interact with other components). It is obvious concluding that **<u>BIM objects' are Modules and CAD objects' are Building Blocks</u>**.

As a result, BIM elements are industrialized, prefabricated, pre-assembled modular components.

8. Manufacturers and BIM

If we think in the most important goal of BIM, it is making building much easier, quicker and interrelated. Anyone could now agree that introducing non-prefabricated and non-standard components is a delay, since it is not aligned with the overall objectives of BIM.

It is also important noticing the difference between an element and an object within the BIM framework, because both terminologies are used:

- Object: They are parametric, which means that the place instance can be freely configured. When you place and object, you are placing an instance of an external file located in an object library.
- Element: Is anything created by a tool in BIM software. All objects are elements, but not all elements are objects.

Here are some of the requirements for considering an element an object:

- Having 2D or 3D geometry
- Material representation
- Parametric geometry
- Connection locations and requirements with other systems
- Performance specifications, such as operating life, maintenance cycle…
- Links to product distribution channels

Makers are introducing virtual pre-fabricated and standard objects on their catalogues for BIM use, because that is the only way admitted for BIM. As we agreed before, all BIM objects are considered modules.

These elements are included in libraries provided by the manufacturers. The advantages of combining BIM with prefab standard components are obvious and have been discussed before.

It is interesting knowing a bit more about BIM objects; the reason why each time more and more manufacturers need BIM objects for creating their buildings is simple: BIM is based on object usage and reflects the real-world behavior and specifications of a product.

And how are those products used? Nowadays, finding an object in a large catalog involves a time-consuming search. If the architect or engineer has a high quality manufacturer's object readily available, the efficiency will improve. Through different platforms, the objects can be in hands of architects.

There are several approaches for exchanging and sharing the models, which can be created by both manufacturers and anonymous people:

- File exchange: Is carried out by exchanging the physical file of the BIM through the transfer of the file either by physical mediums or computer networks.
- Application interfaces: The BIM physical file can be accessed using an API (Application Programming Interface)
- Shared databases: Allows multiple applications access the model data and make use of it.

Figure 10: Development Process for BIM object

9. Designing with BIM in real world

Requirements for building a high quality and accurate BIM object consist of three essential attributes [21]:

- Visual representation: BIM relies on the accurate representation of a building in 3D, and the same applies to the products used in the building.
- Embedded BIM object information: Associating essential product information to the object is a key BIM benefit.
- Modelling techniques: When a modelling vendor creates BIM, the object should be parametric in nature (including a set of rules the object must comply with when the object is modified). A possible example is when the size of a door changes, then the door frame will change too.

BIM design tools provide different libraries of fixed parametric objects. These are typically generic objects based on standard onsite construction practices that are appropriate for early-stage design. As the design is developed, object definitions become more specific as architects, engineers and designers add the different requirements.

It is desirable to define an object once and using it multiple times in the same project. The challenge is to develop an easy-to-use and consistent means for defining object instances appropriate for the current stage of design.

But, how it is designing with BIM in the real world? Traditionally, the different floors of the building are comprised of a series of modules given width. If we look at the core modules of a high building, they are composed by a set of modular dimensions that run all the way up the building. By configuring parametric modules, it is also much easier placing service modules, like elevator´s or stairs´.

These modules are formed by walls, floors and roofs, which are typically composited from several layers of applied materials. In the early design phases it is much more important including essential information (such as the description of the component) rather than specifying composition.

If we have a look at the definition of module, it is a prefabricated and pre-assembled component. Since for designing in BIM is necessary interchangeability, it must be also standardized. As a result, <u>the only elements which enclose a space and meet the requirements are *Modular Building* and *Volumetric Pre-Assembly objects.*</u>

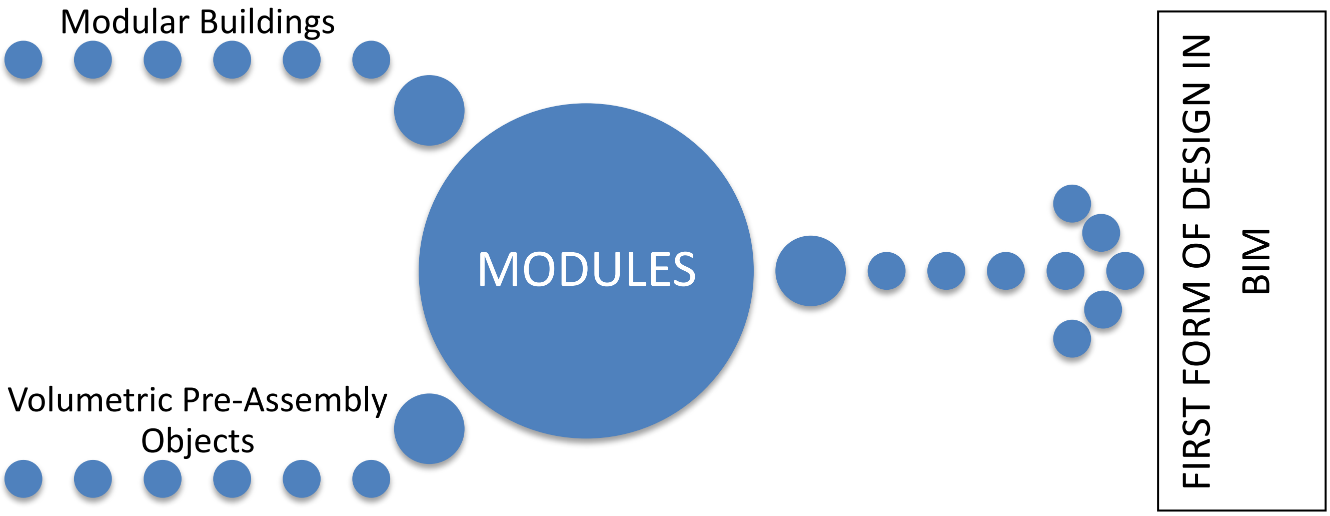


Figure 11: Which type of industrialized components are early modules?

BIM objects can be classified in three different categories:

- Enclosed spaces or rooms (Modules)
- Building Object Models
- Secondary components

Keeping the model as simple as possible is a highly recommended tip, at least for 3D visualization. In later technical documentation, further details can be included, but efficiency is primary.

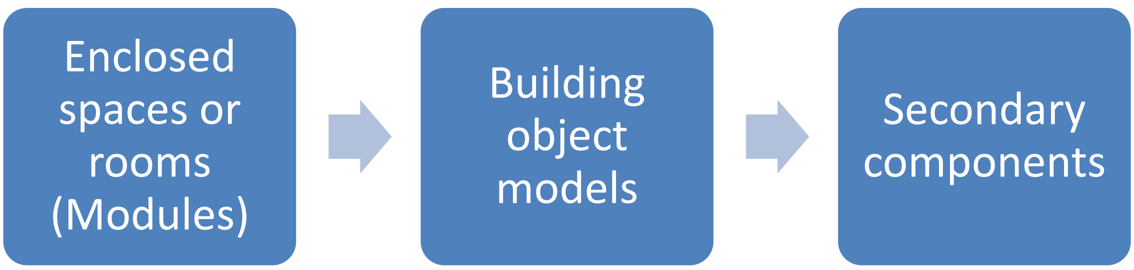


Figure 12: Process in BIM design

Building Object Models are geometric representations of physical products such as doors, windows, equipment, furniture and high level assemblies of walls, roof, ceilings and floors.

For particular design requirements, parametric models of space types may also be represented in libraries. These spatial assemblies can be considered too as Building Object Models.

Each of the BIM design applications also includes other objects such as openings and joints in walls and slabs, connectors, columns and other structural objects. These are considered *secondary components*.

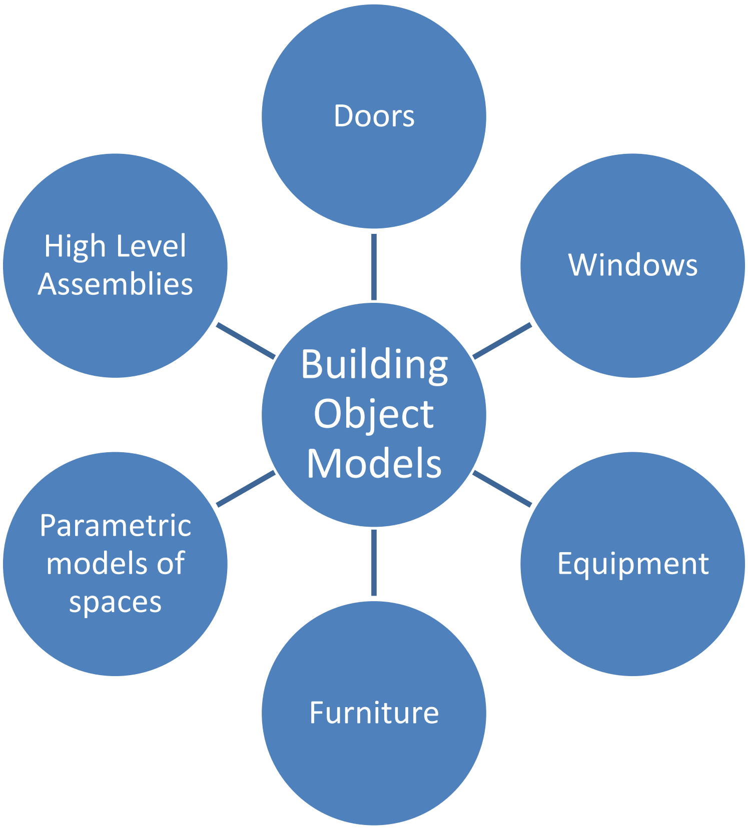


Figure 13: Types of Building object models

According to *BIM HANDBOOK* (Chuck Eastman, 2011), other distinction can be done in terms of the customization of the object.

Standard components can be classified in two different groups: those objects that interact with other objects, such as walls, beams, columns, and other objects that do not need having parametric behavior (bathroom furniture, accessories…).

There is another group, commercial custom-made to their context products: curtain wall systems, complex ceiling systems, cabinetry and architectural metal work.

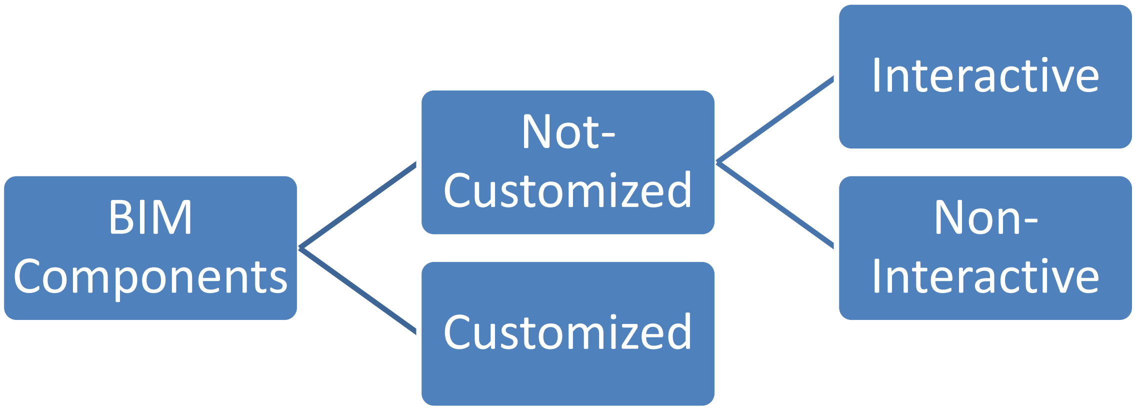


Figure 14: Classification according to the degree of customization

It is important explaining the meaning of customized: it does mean that the component doesn´t have the standard measures, composition or finishes. <u>But in no case means it is not standardized</u>. A customized object maintains the same level of standardization and is fully interchangeable with the rest of components.

10. Correspondence between theoretical and virtual framework

Since we concluded is mandatory using modules when designing in BIM, these components must be prefabricated and standardized (modularity entails standardization).

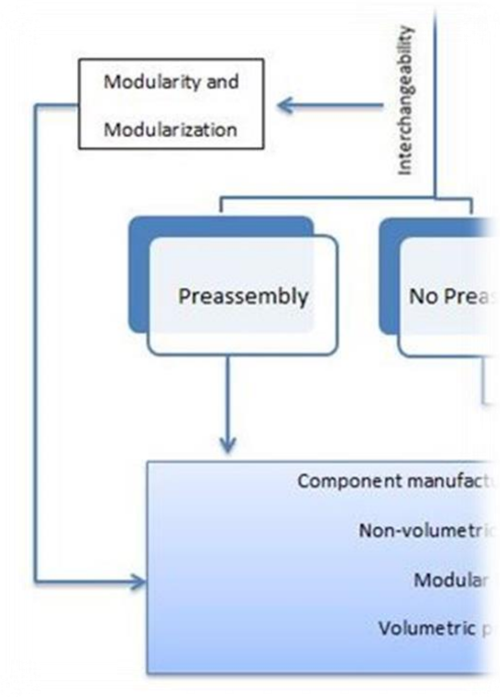


Figure 15: Modularity entails Pre-assembly

According to the ideas exposed before, modularity also entails pre-assembly. Therefore, we can get to the conclusion that there are four different types of industrialized components which can be used while designing in BIM. All of them are considered modules:

- Sub-assemblies
- Non-volumetric pre-assembly
- Modular Building
- Volumetric Pre-Assembly

There is a clear correspondence between *enclosed spaces* created in BIM and *Volumetric pre-assembly* and *Modular Building.* Depending on the size of the volume enclosed and on the degree of completion, the BIM enclosed space can be considered of one type or the other.

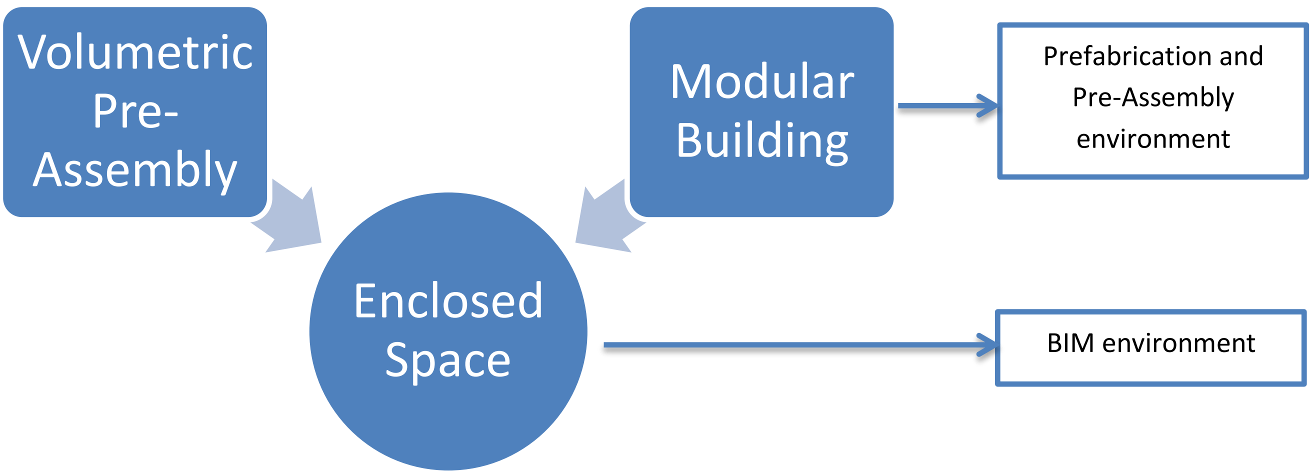


Figure 16: Correspondence in enclosed spaces between theoretical environment and BIM environment

According to objects which do not enclose any space, the theoretical framework shows that *Non-Volumetric Pre-Assembly and Sub-Assemblies* includes those elements assembled in factory, with self-contained functionality and with modularity. There is an obvious relationship with *Building Object Models* and *Secondary components*, both groups in BIM environment.

Depending on the size of the element, this can be considered *Building Object Model* or *Secondary component,* but in both cases is a *Non-Volumetric Pre-Assembly and Sub-Assemblies* components.

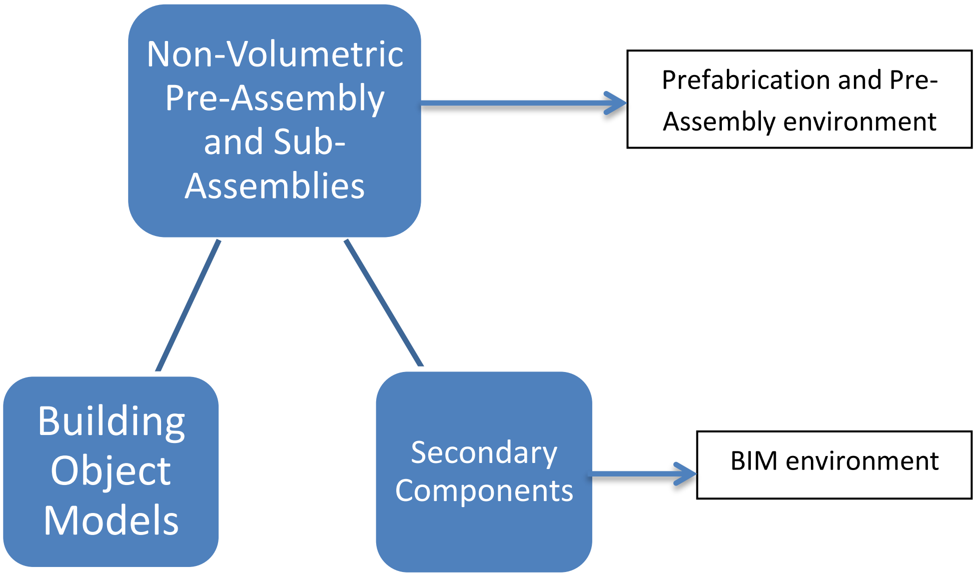
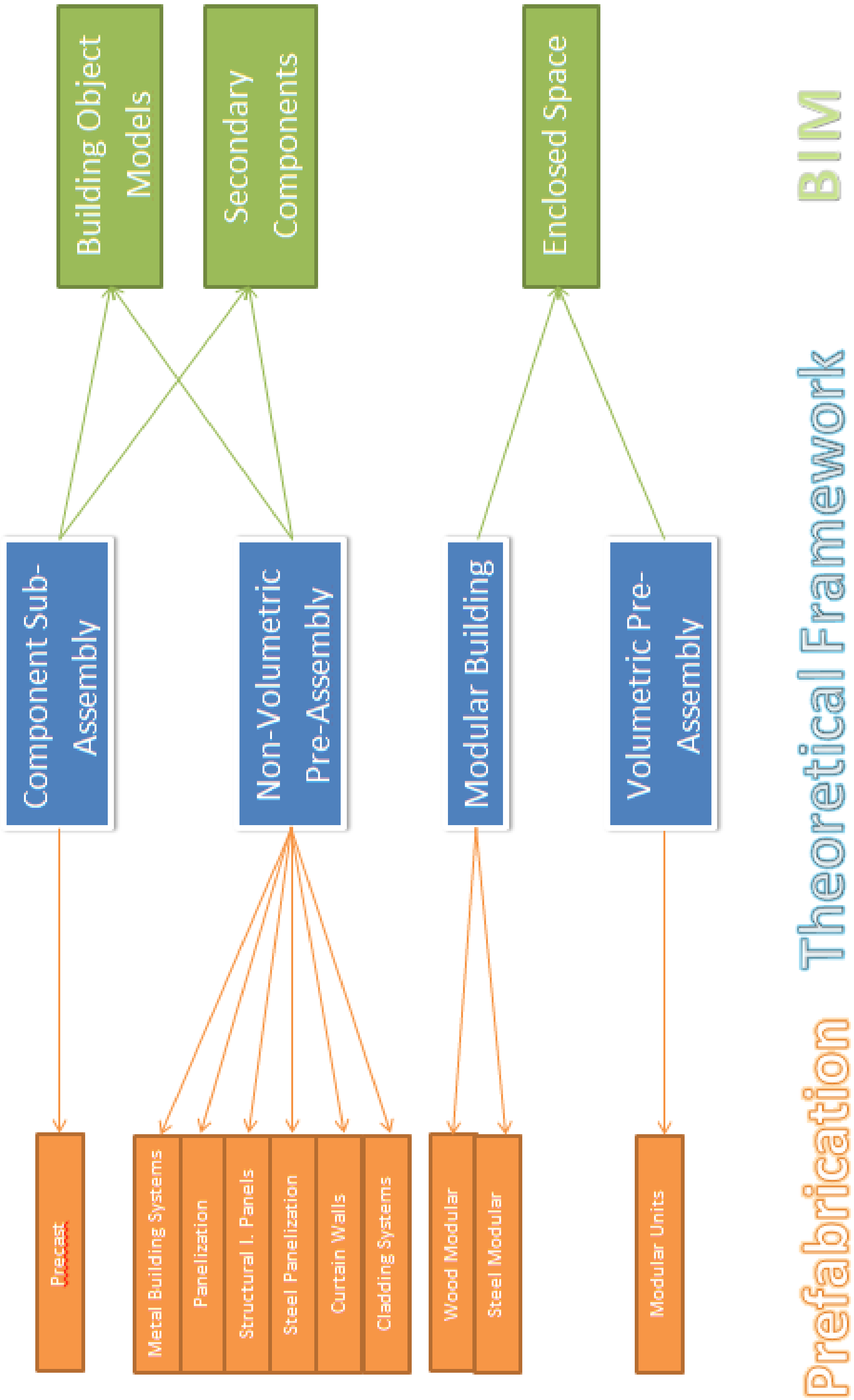


Figure 17: Correspondence in non-enclosed spaces between theoretical environment and BIM environment

11. From Prefabrication to BIM: a complete view of the correspondence of concepts



Building Prefabricated Components: 3D Printing and CNC

1. 3D printing

1.1 Introduction, ¿what is 3D printing?

It is not a single technology, but **a combination of technologies known as "additive manufacturing", based on ink-jet printing technology.** [12] [13]

For simplicity, the media refers as "3D Printing" to any AM process. Unlike traditional manufacturing, which generally involves removal or deformation of material (forging, grinding, milling or bending), **3D printing works by adding material, layer after layer.** The base material can be plastic, metal, sand…

The relation between the virtual environment and the real one is now closer as ever: Before anything can be printed, it is therefore necessary to have a 3D file which models of the object to be produced (this can be created using 3D modelling software or using a 3D scanner, which copies an already existing object).

We can consider three different families of technologies according to the technique used:

- *Using light to solidify the material*: Stereolithography, as it is called, is the oldest technique and also the most precise. Stereolithography uses an ultraviolet laser beam that passes incrementally over the material and solidifies the liquid polymer layer by layer. Manufacturers of dental products or luxury jewelry are the main customers of this technology.

- *Selective Laser Sintering (SLS)*: Based on the use of light to fuse powder granules, one layer at a time. It is specially used for producing architectural models. Powder sintering has the advantage of offering a very wide choice of materials that can be printed: any material which can be reduced to homogenous powder can be produced. Thus, metal can be printed in 3D.

  Using these techniques, powder which has not been fused can be partially reused for later printing, offering massive reductions in material usage.

- *Fused deposition modelling (FDM)*: This technique is used in majority of personal 3D printers. It uses a plastic filament in a heated extrusion nozzle. The nozzle moves and draws the desired object. By rising, it deposits the different layers. The biggest inconvenience is the imprecision, but the advantages are huge: low cost, ease of use, very compact machines and ease of repair.

3D printing has a large tradition with plastics, but in the near future, the amount of printable materials will grow vastly, as lots of research is being done. Available machines at this moment can work with two materials: metal and plastic.

1.2 Why is 3D printing becoming so popular?

3D printing has been a functioning technology since the 80's, but at the moment we are experiencing a real revolution in the field: the reason is that traditionally 3D printing tech has long been the domain of businesses, but we are on the threshold of personal 3D printing.

While this new reality is exciting, it also poses some questions for the future of how we manufacture goods. Today´s consumers require high speed in manufacturing the products and huge customization, but this is not always possible with traditional manufacturing techniques. This, combined with the reduction in 3D printers' prices has led to the present situation.

3D printers are being used to create custom and complex elements while having an economical price. It is a classic disruptive technology: it is simpler, cheaper, smaller and more convenient to use than traditional manufacturing technology.

This technology is not expected to flourish in traditional manufacturing market for a number of years; however many technologies disrupted and changed their industry, like processors. Most disruptive technologies start out inferior than the dominant technology, but they find quickly a market to expand (prototypes in this case).

Another disruptive element of 3D printing is flexibility: the fact that a single machine can create different products compared to traditional manufacturing processes, where special cast is required. Also many steps in the supply chain can potentially be eliminated (distribution, storage and retail).

Obviously, it is easy to dismiss the impact of 3D printing if you focus only in the capabilities at the present moment, because modern highly automated factories perform much better with entirely finished products. However, dismissing 3D printers´ impact is ignoring an important piece of the future of the industry.

Especially in low volume production, 3D printing provides additional value, because development costs are reduced drastically. Also in large production, the economic benefits are evident:

- Is less labor intense
- Uses less material
- Produces less waste

Additionally, as 3D printing allows precise control of the material used, the internal structure can be optimized and precisely designed.

Also research in 3D technology is experiencing a boom at the moment, as some experiments are being made with alternative materials, like chocolate, wood and other organic compounds. Some other materials are more than just a niche alternative, such as titanium. As it tends to harden while cutting, it results in high tool wear. By printing 3D eliminates the problems of machining.

Prototyping new products are the largest commercial application for 3D printing, as it allows testing and touching and testing the products prior to its launch, shortening the development cycle. 3D printing has shifted from prototype manufacture to part production.

Now we will have a look at some of the most successful areas for 3D printing:

- Defense: The required specifications for defense components are durability and reliability. Combination of 3D printing with traditional techniques has allowed not only save money, but also creating a whole plane composed by 3D printed materials.

- Aerospace: As 3D printed materials weight less, they provide weighting reductions, especially important in aeronautic uses. Furthermore, if it was possible to build products and repair broken elements on the Space Station, it would be a huge improvement.

- Automotive: For years, car manufacturers have used 3D printers for prototyping. But at this moment they are starting to introduce this technology in final products, and also the tools they use.

- Healthcare: Adoption of 3D printing in healthcare will need some more years, but early developments to create bones or prosthetic devices have improved. This use is especially satisfactory, as traditionally these elements require high customization. Other research via is building organs with living cells and biomaterials, using the data from medical scans.

1.3 3D Printing and Building

3D printing is the clearest link between the virtual and the real design world and it is important classifying it. Three different types of 3D printed components in construction can be considered according to its purpose:

- Prototyping: This has been one of the first uses of 3D printers in construction industry. It is especially helpful for observing the design details of the building and having an idea about how it will look.
- Small building Components: These components are primarily used for short-run elements, which would be specially expensive to produce with traditional methods
- Big building Components: These elements have a great importance in the operation of the building. In the near future, these components should be produced in longer runs.

An analogy can be made with other important big and changing industry: smartphone industry.

At this moment, Google is working in *"Project Ara"*, a highly customizable smartphone, which is composed by different modules which can be interchanged easily. At this moment, the first modules created with 3D printers are appearing into the market.

This project is producing a whole revolution in the industry and helps to understand in which direction will evolve the rest of the industries.

1.3.1 Small Building elements

Traditionally, small building 3D-printed elements are created at an off-site location, following standardization and prefabrication criteria. These components are made of plastic or metal and can be considered "accessories" of much bigger components.

Since 3D-printing permits creating a complete component from a single material piece, the elements have self-contained functionality and can be considered as modules.

1.3.2 Big Building elements (Contour Crafting)

Although there is not too much information about 3D printed houses in construction industry, a new technique called "*Contour Crafting*" has been developed Behrokh Khoshnevis, from the University of Southern California. Of course, it is possible to create big components with traditional 3D printing methods, but this has not been yet applied to construction industry.

According to *Automated Construction using Contour Crafting-Applications on Earth and beyond (B.Khoshnevis; 2007) Contour Crafting (CC*) is a recent layered fabrication technology that has a great potential in automated construction of both whole structures and sub-components. It is based in an additive fabrication technology, which uses computer control to exploit the surface-forming capability of troweling to create smooth and accurate surfaces. Compared to other layered fabrication processes, the advantages are:

- Better surface quality
- Higher fabrication speed
- Wider choice of materials

The layering approach enables the creation of various surfaces using few trowel tools, combining extrusion (for the object surface) and filling process (for the core of the object).

For application in construction, a gantry system carrying a nozzle moves on two parallel lanes installed at the construction site, enabling the construction of various houses at the same time. [16]

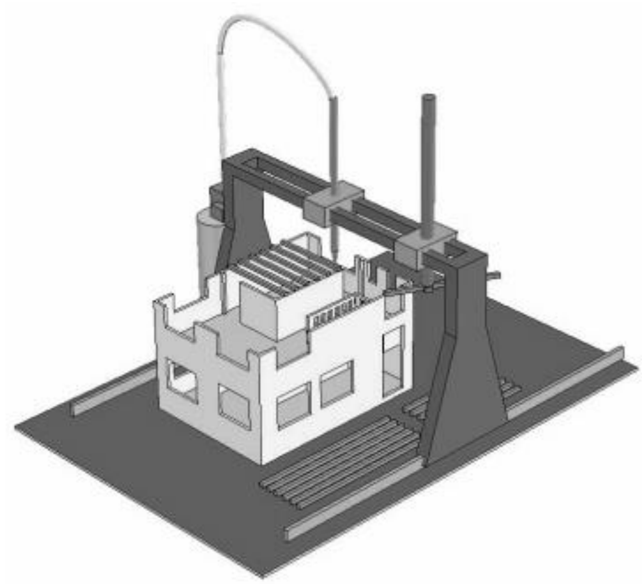


Figure 18: System for building houses with CC [16]

Which are the main aspects of this building technique then? On one side flexibility, which allows creating both functional and visually attractive structures, that would be difficult to create otherwise. The availability of materials is large, enabling the combination of them in different surfaces to provide new properties. For example, by combining concrete with additives, better construction can be achieved.

In this moment, the state of development of the technique is at an early stage, but lots of experiments are being done to increment the variety of shapes and the materials available.

Towards improving the strength of large housing structures built through CC, the use of reinforcements has been investigated. Due to the high pressures in CC compared to other layered techniques, the extrudate adheres to the coils without causing any discontinuity. It is also possible combining “layered” materials with “rigid” ones, such as steel mesh, for reinforcement purposes. [16]

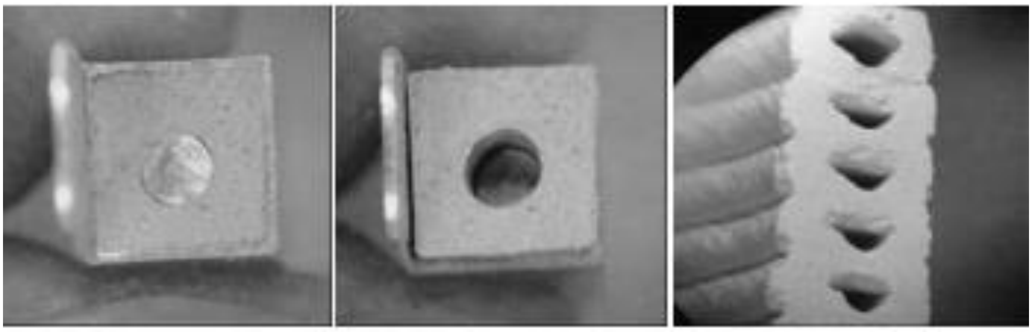


Figure 19: Depositions with hollow cavities [16]

Also, depositions with hollow cavities can be achieved, including various shapes. It is also possible to extrude reinforcement materials, such as epoxies or various concrete based compounds through these cavities for added strength.

As we said before, this technique is at an early stage and lots of research is being done at this moment. New nozzles are being developed which allow co-extrude both outer sides and filler materials, achieving the construction of a wide variety of curved structures as designed by architects.

Instead of using just a platform with a nozzle, another alternative involves the coordinated action of multiple mobile robots, because the advantages are clear:

- Ease of transportation
- Ease of setup
- The possibility of concurrent construction where multiple robots work on various sections of the structure to be constructed
- Possibility of scalable deployment of equipment

A construction mobile robot can use a joint structure and can be equipped with material tanks and pumps. At the end effector of the robot, a nozzle would be placed allowing reach both the ground and the top of the wall. [16]

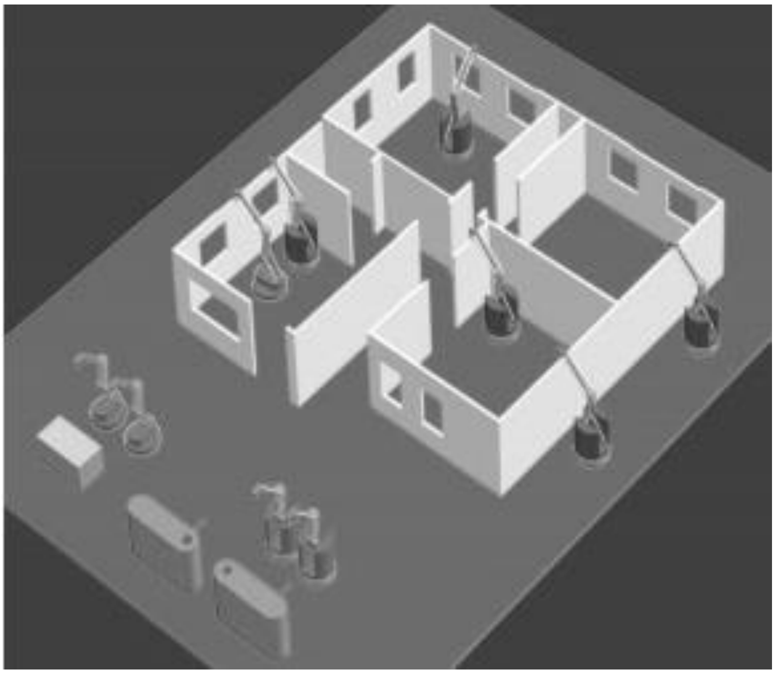


Figure 20: Ideas for contour crafting and robots [16]

Besides, there is not necessary any mobile structure in the robot. By placing a position sensor in a fixed location and the retro-reflectors in the robot arm, it will stop as soon as the target is reached. Once it reaches a predefined post, the robot anchors itself by extending some rods from its bottom, and starts the fabrication from the last point fabricated while at the previous post. [16]

Roof construction does not need always support beams. Support less structures such as domes may be built with robots, but for planar roof the process is completely different. The beams, which have a sheet attached, are positioned by robots.

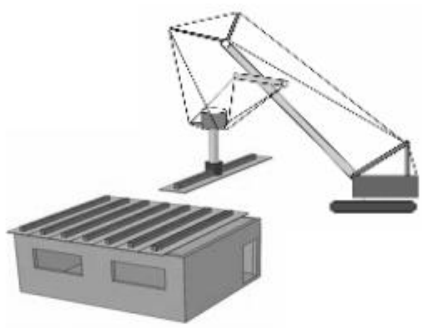


Figure 21: Idea for planar roof building *[16]*

The potential of this technology is so high that some futuristic applications have been explored, like for example constructing houses in Mars or the Moon. In the moon, the solar power is available, making possible implementing solar panels within the robots. [16]

As we did before, it is important defining CC within the theoretical framework developed before. Is Contour Crafting a process involving prefabrication? No, it is not. The components are created in-situ, not on a site different to its definitive location.

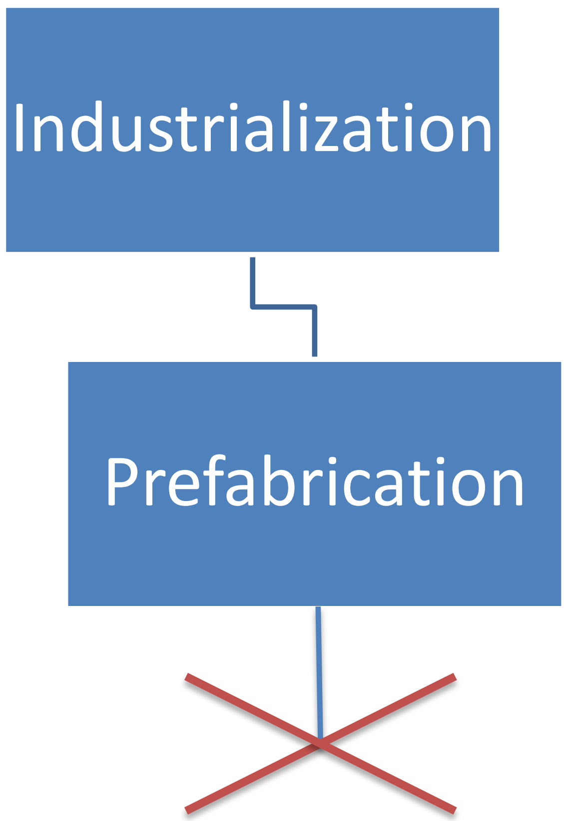
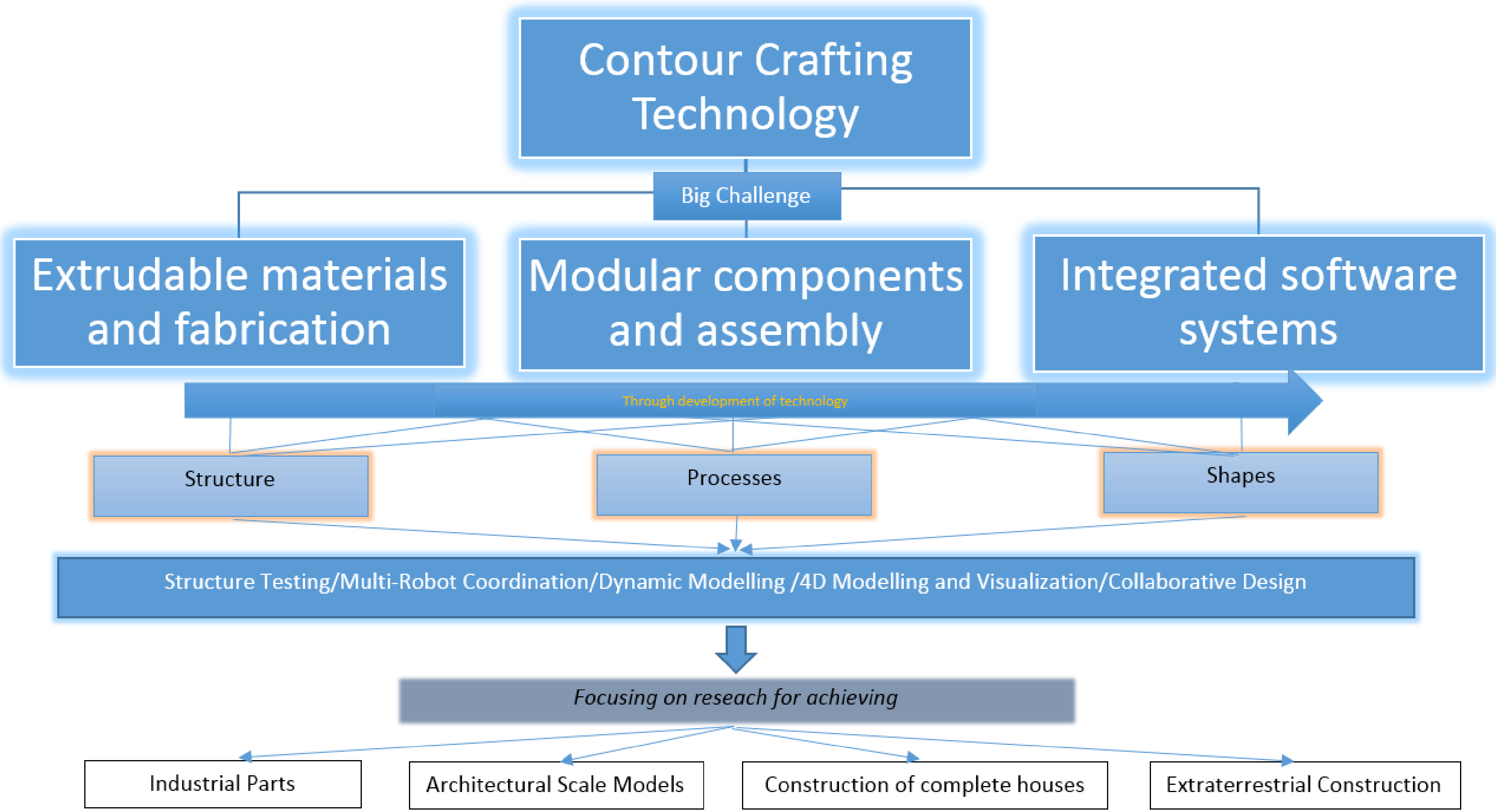


Figure 22: Demonstrating CC is an industrialized process, but not prefabricated

Since prefabrication is not included in the process, there is no use to determine if the component is standard or pre-assembled, or if it is possible to interchange different components.

We can state that CC is an in-situ technique which uses industrialized techniques, but under any circumstance can be considered an off-site technique or a prefab one.


Contour Crafting Technology
Big Challenge
Extrudable materials and fabrication
Modular components and assembly
Integrated software systems
Through development of technology
Structure
Processes
Shapes
Structure Testing/Multi-Robot Coordination/Dynamic Modelling /4D Modelling and Visualization/Collaborative Design
Focusing on reseach for achieving
Industrial Parts
Architectural Scale Models
Construction of complete houses
Extraterrestrial Construction

As we have seen before, Contour Crafting is a challenging technique which will experiment great changes in the near future, since it is in development at the moment.

The big challenge is to combine the capability to build modular, to integrate the software and to produce extrudable materials, in order to make this technique feasible and realistic.

But, how can technology evolve? My supposition is that CC will evolve to offsite location, due to the better conditions for setting concrete. Thus, investment in research and technology for this purpose is required. At the moment, only simple shapes and structures can be created, although with the installation of robots the future of the technique is very promising.

Due to its speed and its ability to use in-situ materials, there is a high potential for creating low-income housing.

1.3 Consideration in the theoretical framework

In this paper, I will focus in the second group, since I found it much more interesting for building purposes. This table will help to clarify the questions about this group:

Question	Statement in theoretical framework	Conclusion in 3D Printers' framework
Can 3D printing be considered as Industrialization?	According to Industrialization definition, manual labor processes are replaced by mass production and assembly lines.	Yes, 3D printing is an obvious industrialization of building process, as manual labor is substituted by a machine.
Can 3D printing be considered as Prefabrication?	Prefabrication is the manufacture of parts of the final structure on a site different to its definitive location.	It depends. 3D printers can be or not placed in the Building site, depending on the needs.
Can 3D printing be considered a Standardized process?	Standardization ensures accurate fit and interchangeability between the interfaces of the elements.	It is not clear yet, but it is supposed that it is. Since we are in an early development stage of 3D printing, some conclusions cannot be categorically stated.
Can 3D printing be considered a Pre-Assembly process?	Pre-assembly is the process by which various materials are joined together at a remote location.	In some early examples of 3D printed components, most of small elements are pre-assembled, since they leave the factory "finished". But in CC, we cannot state the same.

Figure 23: Approach to the classification of a 3D printed component

It is clear that 3D printing cannot be totally classified within a category of the theoretical framework, since there are a lot of variations within 3D printing: are not the same the big components and small ones.

Is 3D Printing an on-site technology or an off-site one? It is neither clear because of the variety of components available. Whilst big components cannot even be considered prefabricated components, small components are prefabricated, standardized and pre-assembled. Within pre-assembly category, small components are classified as sub-assembly elements in the theoretical framework.

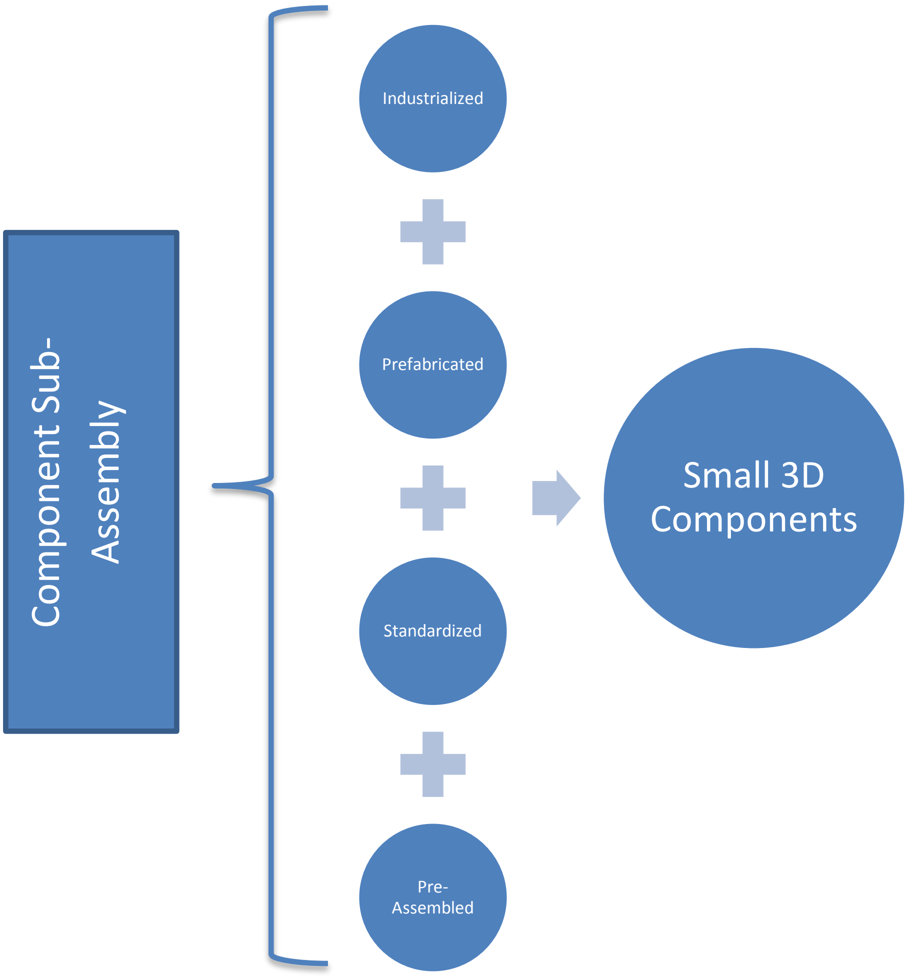


Figure 24: Classification of Small Components within theoretical framework

In relation to modules or building blocks, 3D printing elements will always be considered modules, because of the reasons here exposed:

- Connections are required to join the different elements of the building. It is necessary also considering the space for introducing the plumbing and other services installations. <u>They interact with other components.</u>
- When building houses with 3D printers, complex components are printed. As a result these elements use to <u>have self-contained functionality</u>.
- These components traditionally have standardized interfaces; this is because <u>they are designed for being interchangeable</u>.

As we said before, 3D printing is one of the clearest examples of relationship between the virtual and the real environment. It would not have any sense designing building blocks with 3D printers, except for very specific and short-run components.

1.4 Small Components vs. Big Components

	Small Components	Big Components (CC)
On-site		X
Off-site	X	
Industrialization	X	X
Prefabrication	X	
Standardization	X	
Preassembly	X	
Modularization	X	
Module	X	X
Building Block		

2. CNC Machining Technology

Manufacturing methods vary according to material and manipulation, but there are generalized methods by which materials are shaped to achieve an output. Machining is the process of removing material through mechanical operations. Some examples of the machining tools are saws, drills, mills and lathes.

There are three methods of CNC machining:

- Water-jet cutting uses high water pressure to deliver abrasives that cut through materials. The advantage of this technique is its precision, being able to cut in x-y axis and cooling the material at the same time. Metals can be cut without thermal stresses and it is not necessary using clamps with other pieces.
- Plasma cutting is used mainly for metals and ceramics. Instead of using water, this technique uses concentrated heat to cut with high precision. The main disadvantage is the deformation that can be produced due to high temperatures.
- Laser cutters remove material through a light amplification by stimulated emission of a radiation beam of light.

Plasma cutting is the most affordable of the three methods, but is also the most problematic with heat issues. Laser is the most precise, but it also has problems with heat deformation. Water-jet cutting is the only one that does not have any issue with deformation, but it is much slower and more expensive, since maintenance is higher.

Types of CNC machining tools:

- Driller: One-axis machines that cut by a rotating bit pressed in a vertical direction. Punching is used in metal for doing holes in any pattern.

Figure 25: Example of Drilling machine [23]

- Miller: Is the most flexible tool of all operations. With the availability of 6 axes machines', most of the shapes can be achieved in several materials, like wood, metal, stone, foam or other material.

Figure 26: Example of Milling machine [23]

- Lathes: They turn the base material around one axis while a tool removes material and creates circular defined elements.

Figure 27: Example of lathing machine [23]

3. Other prefabrication techniques

3.1 Molding

Molding includes deforming, casting and pressing technologies. The processes of molding are defined by the type of stresses induced into the work-piece while being cold, because it causes a permanent deformation and the final shape.

Casting uses a material in liquid state poured into a mold to achieve the desired 3D object. The materials of the molds are various depending on the use that they will be given and can vary from wood to plastic, ceramic or foam. Most of the times, casting requires objects to be finished by machining, because the tolerances are high.

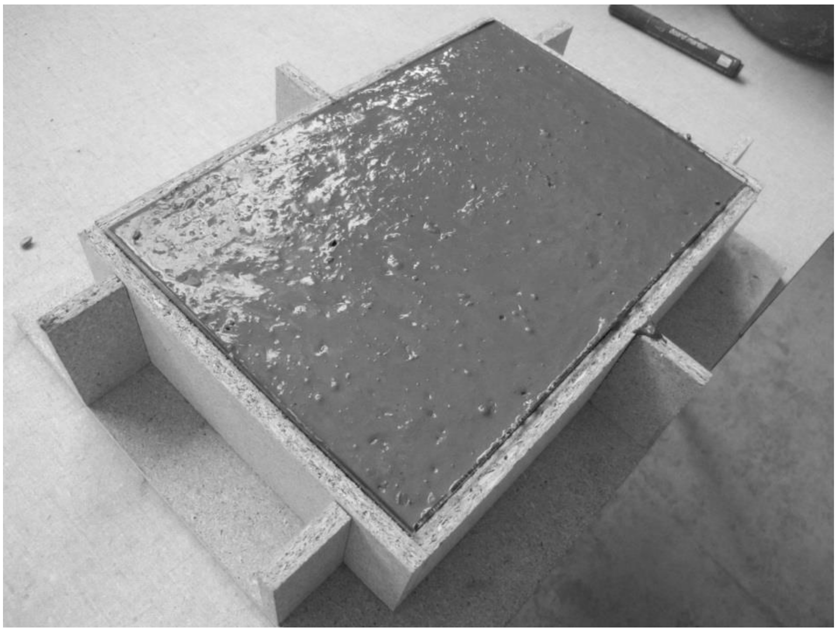


Figure 28: Example of concrete casting [18]

Injection molding is used with thermoplastic polymers and has a large acceptation at this moment. Other methods like thermoforming or vacuum forming can achieve the same result, but they are not as accurate as injection molding.

3.2 Fastening

For this process, it is required previous operations like machining or molding. It is considered the final process before the final product leaves the factory. The difference between fabrication and other processes is fastening.

There are three ways of fastening in the industry:

- Using metal bolts, screws, rivets, nails and staples. Just as important as the fastener is the preparation of the pieces, keeping the tolerances low and considering the size of the holes.

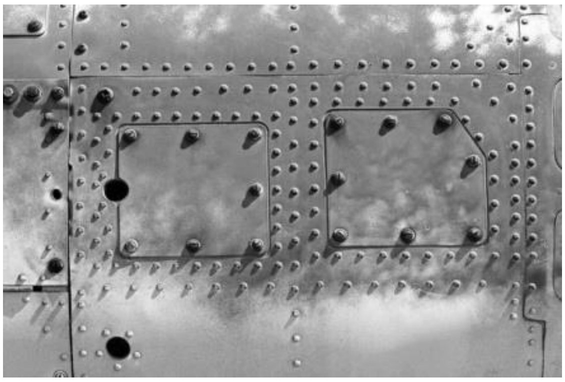


Figure 30: Metal Bolts [23]

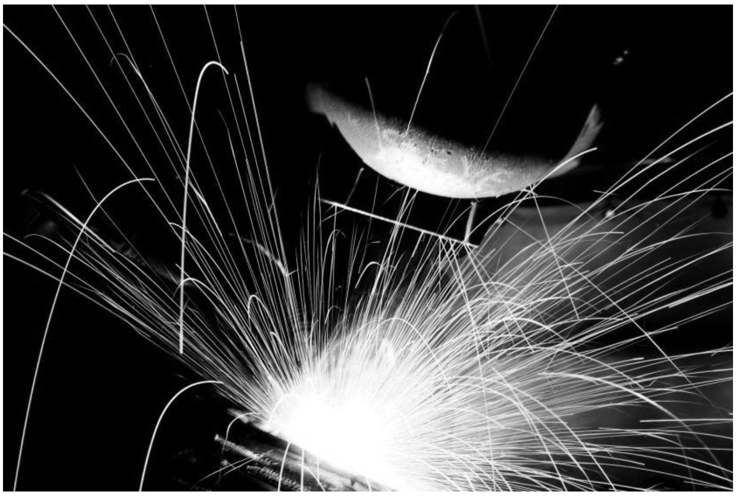


Figure 29: Welding [23]

- Welding does not require any fastener, and consists in joining metal pieces by heating them. Welding is used for structural and high loaded conditions in which rigidity of pieces is very important. There are several techniques of welding (MIG and TIG) and types of welds, which are used depending on the element that is welded.

- Adhesives are used in light load applications, although there is lots of research to create high-performance glues. They are really common in glass, ceramics, wood and polymers, but they have the disadvantage of not permitting disassembly or recycling.

4. Conclusions

From the first moment, this paper is focused in combining industrialized processes with virtual environments, in order to achieve all the benefits of this technique. As we have seen, Contour Crafting is a process whose degree of completion and post-work is the highest possible, because of several factors:

- It does not need human resources to construct the building
- It does not need transportation, so lot of time is saved
- It does not require standard shapes or dimensions, because any shape can be achieved

This leads us to believe that 3D Printing cannot be considered a fully Prefabrication process. Yes, it is an industrialized one and it also produces modules, but it does not always align with the definitions explained in the theoretical framework.

CNC machining technology is obviously aligned with the concepts exposed before. It is an industrialized technology, which can produce a wide variety of prefabricated components: pre-assembled, not pre-assembled, standardized, not-standardized…

And now the question is: what is 3D printing? It is obviously an industrialized process which can entail prefabrication or not, it depends. What does it depend on? On the type of 3D printed object:

- Big Components (CC): They are industrialized modules, made form concrete, which do not entail prefabrication.
- Small components: They entail prefabrication, pre-assembly and standardization. As a result, they are modules.

<u>I suggested before that the only way for an industrialized component to be a module was being prefabricated, pre-assembled and standardized, but it is not. Not-prefabricated components can also be modules and satisfy all the requirements of them.</u>

Contour Crafting is now at a very early stage and because only first experiments have been made, it is not convenient to categorize the technology within an immovable framework. Since, from my point of view, Contour Crafting will evolve to prefabrication (like the rest of the industrialized processes did), I will also consider including it in the prefabrication category.

And which are the reasons for considering CC to evolve from onsite to offsite location? Very simple, because concrete requires specific conditions for setting, and a factory protected from rain and other external factors is a much better place for doing the process. Even at the factory, the advantages are obvious respect to cast technology: it permits achieving more complex shapes; it does not need a cast (entailing money savings); it is much faster.

Buildability, Flexible Housing and Mass Customization

1. Buildability

1.1 Definitions and concepts

The are lots of accepted definitions for buildability, but one I liked most is "**A design philosophy, which recognizes and addresses the problems of the assembly process in achieving the construction of the design product, both safely and without resort to standardization or project level simplification**" (Moore, 1996). In a much simple way, it is the technique to facilitate ease of construction.

The main difference between constructability and buildability is that the first one is a design-oriented concept, while the second one is concerned with the whole project process. Despite of this, the two concepts are used interchangeably in most situations.

For this reason, this paper will make no difference between both concepts.

1.2 Design for Buildability

The principle entails bringing together the technical experience of a Builder/Constructor and the design experience of Architects and Engineers early enough at the design stage of the project. The technical efficiency in design resultant reflects in many areas [17] [18]:

- Geometry/layout of the building: The general rule is to use simple shapes with lower perimeter/floor area ratios, with reductions in material and labor requirements.
- Design details: This includes taking care of the fitments and positioning of services, structural system or roof system.
- Construction methods: The principal aim is to achieve ease of construction, minimize waste and optimize site labor and plan utilization.

The development of buildability concepts can be divided into three different phases:

- Design rationale: This concept is focused with emphasis on design for ease of construction and site productivity.
- Life-cycle concept: It is a total project concept; from planning to maintenance.
- A methodology of new production philosophy: Integration of buildability with other philosophies, such as lean construction.

Since design is the first step in construction, some design for constructability tips will be provided:

- In the concept design, it is necessary reducing part count.
- In the detail design, maximizing part symmetry will help to reduce inefficiencies.
- Design parts to be self-aligning and self-locating. This includes allowing generous clearances but avoiding parts jamming during insertion.
- Eliminate redundant parts
- Eliminate fasteners as much as possible: They can be problematic for standardized and quick production.
- Eliminate unnecessary welding which does not serve any engineering purpose.
- Design for rigidity rather than being tempting to over-engineer for inherent strength.
- Reducing as much as possible material mass equals reducing cost. It is not incompatible with designing for rigidity.
- Consider using structures and frames to accommodate cables and plumbing instead of doing posterior repairs.
- Welded fabricated members and parts create a strong rigid structure which eliminates the need for fasteners. A very useful guideline is “if it is not moving or adjustable and transportation is not an issue, fix it permanently”.

1.3 Buildability and BIM

In case of using BIM [14], it does improve buildability in three different dimensions:

- Space review: BIM provides a high performance solution for reviewing the integrated design content. Visualization is a good approach to enhance the efficiency of identifying poor design about spatial location.

- Measurement review: If it is not possible to handle the relationships among the plan, elevation and section, the errors of measurement annotation will make problems after construction. Utilizing BIM technology, checking measurement is easier than before and designers enable to ensure the consistency of the design through BIM because of the database.

- Clash detection: Sometimes, it is difficult finding the problems and conflicts in the engineering drawing. During modelling BIM model, the modeler can utilize the clash detection function to find potential conflicts.

When trying to approach to buildability, there are two BIM design models:

- Design intent model used by the architect
- Constructability model used by the contractor

A BIM design model can generate an efficient, highly coordinated set of contract document, schedules, reports, links and images. Its overall purpose is to assist in the design process and for the production of accurate documentation for describing the building.

The constructability model combines the architecture model with a structural model, providing a core data as the basis for adding further information. It contains both architectural and structural components such as foundations, exterior walls, ceilings, columns, beams, but generally not small elements like bolts and connectors. The intent of the constructability model is to simulate the building in 3D to describe the way it will be built.

The design model is not usually the same as the constructability model although if organized with more flexibility and foresight could morph into a constructability model. The relationship between both models has a vital importance, making possible the appearance of three scenarios:

- Two completely different models: forces the contractor to construct a BIM model for his own use
- The design model can be handed by the contractor with assurances that he can continue developing it for the constructability model. It is sometimes risky, as the contractor is assuming the information he gets is correct.
- The reality is a middle point of both models. The architect might give the contractor a copy of the BIM model he uses, representing a basis for further constructability model.

Now, buildability tips of most popular components will be exposed:

1.3.1 Structural Steel

By modelling the structure in 3D with all detailing of nuts, bolts, welds and plates is not sufficient. Additional requirements should be met:

- Automated and customizable detailing of steel connections, by incorporating the ability to define rule sets for the connection types.
- Built-in structural analysis capabilities, including finite element analysis.
- Output of cutting, welding and drilling instructions directly to CNC machines.

1.3.2 Precast Concrete

Modelling precast concrete is much more complex than modelling structural steel, because precast concrete pieces have internal parts, greater freedom in shapes and lots of finishes. These reasons explain why precast BIM software was launched later than structural steel software.

These requirements should be met when designing:

- The ability to model pieces in a building model with geometric shapes different from the geometry in shop drawings. All precast pieces are subject to shortening and creep, what means their final shape is different from the produced one.
- Surface finished and treatments cannot simply be applied to faces or parts, but often have their own geometry, which may require subtraction of volume from concrete.
- Sometimes, concrete mixes are used to provide custom colors and surface effects; as a result, the software must be able to manage the volumes required for each type.
- Specialized structural analyses of individual pieces are required.
- The grouping of precast piece´s constituent parts must be done according to the timing of their insertion.

1.3.3 Curtain walls and fenestration

Curtain walls include any wall closing system that does not have structural function and that does not carry any gravity loads in the foundation of the building. Fenestration includes all custom-built windows.

It is important defining the connections to the structural frame of the curtain wall systems. The joints have also vital importance; as they are susceptible to expansion and contraction due to changes in temperature, they must be highly detailed to allow free movement without compromising insulation. Generally talking, detailed assembly and piece fabrication details must be provided in curtain walls systems, since tolerances are minimal.

Since curtain wall systems are a very important part of the building, relevant physical properties of the wall and its components must be provided.

1.3.4 Mechanical, electrical and plumbing

Electrical communication cables are largely flexible, but the conducts may not be, which means their layout must be coordinated with other systems.

The most generic requirement for these systems to be supported by BIM is that their location, orientation and routing in space must be carefully coordinated. Most of the time physical clash detection is available in the project, but sometimes called “soft clash detection” is also required (checking that minimum spaces are maintained between the different services).

A second generic requirement is the grouping of objects for production and installation logistics, by numbering components according to:

- ID of the piece
- ID of the production group
- ID for installation spools

Obviously, neighboring duct sections should adjust when changes are made to individual sections or to a whole duct. When a duct or pipe that penetrates a slab or wall moves, the hole in the slab should also move.

2. Flexible Housing

2.1 Ideas about modularity and flexible housing

We can classify building elements from the most durable to the least:

- Construction Site: Eternal
- Structure: approximately 50 years
- Skin (roof and wall enclosures): 15 to 20 years
- Services (plumbing): They are usually updated every 7 to 15 years
- Space (interior partitions, doors, ceilings…): Volatile, changed every time a new resident appears
- Stuff (wall paper, paint…): Very volatile

So just having a look to see what happens in a building when capital is invested over a 50 year period: The structure expenses are huge because of three generation of services and various generations of space plan changes. This model of consumptive development requires buildings to be demolished every 50 years and new ones to replace them.

It must be considered another way of building, investing in more durable and higher quality methods for the life of the facility. Most of the materials considered as “durable” are casted in situ, so it´s not always financially feasible building with these materials.

But buildings become old and need repairs regardless of their construction type: replacing service and enclosure systems, adapting the building for safety regulations, refurbishing... Therefore buildings need to be designed with materials that can be recycled or reused in future buildings. There are four design criteria.

2.1.1 Designed for disassembly

This strategy entails that prefabricated elements may be assembled in a factory and then reassembled as larger components onsite. At the end of their useful life these components may be disassembled for rebuilding elsewhere.

The standardized allow for either reuse on a different building or to be put back into the supply chain. But this kind of design is difficult as it goes against the construction conventions.

The strategy is clear: providing a support structure in which building units may be inserted or removed over the time in order to accommodate the different changes. Flexible elements can be classified in two categories

- Support-level elements: Common to all users. They include structure, enclosure and services. Generally their position cannot be modified throughout the life of the building, as they are necessary for the correct structural operation of the building.

- Infill elements: Detachable units from supports, so users can specify how the space will be divided. They can be changed every 10-20 years on average and include interior space partitioning, kitchen and bathroom equipment and finishes.

2.1.2 Designed for reuse

As a strategy, it consists on reusing as much of the building in its existing forms as possible. Prefabrication offers opportunities to expedite the design for the reuse paradigm. Factory-based production allows regulating the use of recycled materials into new products.

Other great opportunity provided by offsite fabrication is the ability to identify materials for their capacity for being recycled.

2.1.3 Designed for temporality

Disaster relief shelters can be taken as an example of temporal buildings.

2.1.4 Designed for change

There are a lot of reasons to introduce changes in housing such as changes in lifestyle or changes because of financial or life circumstances. Design for flexibility can be considered in two approaches:

- Soft flexibility: Users determine the adaptations.
- Hard flexibility: Architects make decisions regarding the way in which adaptation will occur, but sometimes this method creates more obsolescence than it does to eradicate it.

Walls, roofs and floors in contemporary construction today are not adapted to change. When some element is prefabricated but does not allow changes later, a big potential is being missed. Inflexibility in building systems leads to costly changes later, but prefabrication can solve this problem by anticipating it.

2.2 Flexibility and adaptability ideas

The concept of flexibility is defined as the capacity of buildings for physical change and adaptation according to changing circumstances. Flexibility as an inclusive concept covers the related concepts of adaptability and typological variety and it is achieved by designing the fixed elements, which are the structural system and the servicing of a residential block in a way to allow change. [20]

Adaptability in the residential context refers to allowance of variety of architectural configurations in accordance with diversity of usage.

Flexibility should also be considered in two different approaches:

- The ability of the project to offer a variety of choices in housing types prior to occupation.
- The ability to modify the structure of the house while occupation and to adapt to changing situations.

The initial flexibility is a response to the idea of designing residential blocks appropriate for diverse users, and should be considered as a part of the initial design. The second issue is the flexibility offered by the structural system and the service spaces, the permanent components of the buildings (also called as permanent flexibility).

There are different methods to achieve flexibility and can be examined under four main themes: structural system (location of load bearing walls and columns), service spaces (access system and organization), architectural layout (variety of unit types and spatial distribution) and furnishing.

2.3 Soft and hard analogy

The projects which are examples of soft use allow users to make changes according to their needs and wishes in the time. Architect works on the background. In hard use examples, architects take decisions and determine the possible changes or adaptation for users over time.

Hard forms are those one which are specifically designed for flexibility, as it operates in the foreground in terms of importance. The construction technique becomes important in determining the housing design. [20]

On the other side, soft form is the stuff that allows flexible housing in a manner not completely controlled. It is necessary to emphasize that hard systems can be mainly applied in housing with limited space, whereas soft ones are appropriate where there is plenty of space.

2.4 Areas of innovation of flexibility

- Structural system: There can be considered 3 different types of structures [20]:
  - Base structures: Accommodates the design idea of incomplete buildings and focuses on permanent elements (structural elements, access units and servicing).

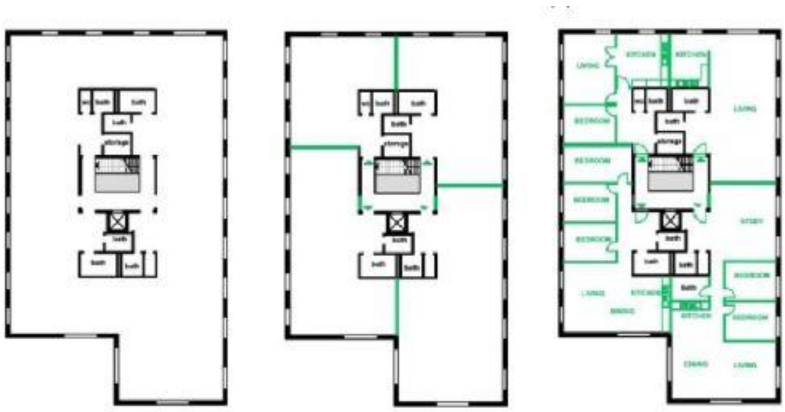


Figure 31: Example of base structure [20]

  - Polyvalent organizations: Rooms without labels, whose dimensions are appropriate for different uses. The modules have standardized dimensions but it´s possible to join modules together or dividing modules into smaller ones. Hard form but soft use.

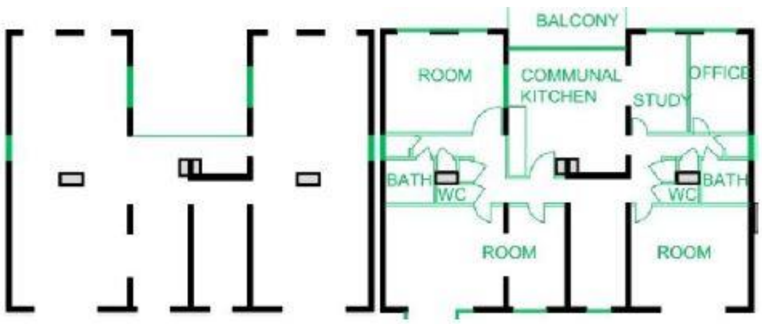


Figure 32: Example of polyvalent organization [20]

  - Both: Adopt two approaches in relation to structural system

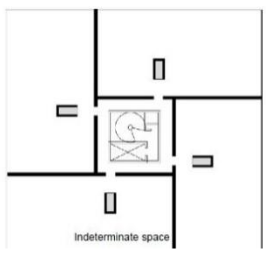


Figure 33: Combination of both (Base and polyvalent) [20]

- Service spaces: The position of service spaces can be part of the structural system or designed separately. It is very important the placing of the service spaces, as it determines the ability to access so they can be updated, as well as the position of the kitchen and bathrooms.

- Architectural layout: Flexibility of architectural layout depends on the configuration of the permanent components of the buildings. The architectural layout can be divided into 5 categories [20]:

    - Slack space: Free space which can be included to the house itself.
    - Vertical/horizontal additions
    - Expanding: The building is a base structure and the building´s envelope can be extended.
    - Joining and dividing units: Combination of units to get larger ones. The structural elements should be included in the units.
    - Shared switched room
    - Divisible/joinable room: Combination of rooms to get larger ones. Structural elements should not be included inside the units.

- Furnishing: Furniture can serve as a separator or compact unit that accommodates functions as well. Furnishing for flexible using can be achieved by using furniture as a surface or as a functional unit.

3. Mass Customization

3.1 Introduction to Mass Customization

According to "Approaches to mass customization: configurations and empirical validation" (Rebecca Duray/Peter T.Ward/ Glenn W.Milligan/William L.Berry, 2000), **mass customization is a manufacture technique which combines the unique products of craft manufacturing with the cost-efficient manufacturing methods of mass production.**

The practice of mass customization does not fit with the conventional paradigm of manufacturing management. Traditionally companies choose processes that supported the production of either customized crafted products or standardized mass-produced ones.

Mass customization is supported from a three dimensional perspective: product design, product process design and supply chain design.

A customized product is designed specifically to satisfy the needs of a particular customer. It is important to difference variety from customization. Customization stands for the specific product which satisfies the customer, while variety means that the customer has a higher number of products to choose which can adapt to his necessities.

If the customers are involved in the early design stages of the product, this will be highly customized. In opposition, if they involve just in the final assembly stages, that degree will be lower. <u>Three different levels of customization can be distinguished</u>:

- Pure customization: Furnishes products designed and produced from scratch for individual customer. It includes the customer in the entire cycle of the product.
- Tailored customization: The basic design is altered to meet the specific needs of a particular customer. The customer is not in the whole production process, just in the "modification" phase.
- Standardized customization: A final product is assembled from predetermined set of standard components. The customer penetrates the assembly through the selection of the desired features from a list of options.

Many authors argument that modularity is the way for achieving mass customization, because modularity provides a mean for the repetitive production of components and allows part of the product to be made in volume as standard modules with distinctiveness achieved through combination or modification of modules.

3.2 Technical challenges of Design For Mass Customization (DFMC)

- Optimizing the reusability: One of the key enablers of mass customization is to derive the most economic building blocks and maximize their applicability. It is achieved by reusing the design, production capability, tooling, supplier base, process plans and manufacturing logistics.

- Synthesizing a unified product family architecture: The product family architecture (PFA) provides the basis for the characterization of customer need, which can be fulfilled through a configuration of modules.

- Facilitating the Meta level integration throughout the design process: Realization of mass customization requires not only the integration of the design process from an organizational perspective, but also the provision of the contextual framework and the system integration architecture.

A "family-based" design is the one which exploits the similarity of design and manufacturing processes. The similarity captured is then built into a PFA in order to increase the design rationalization. By grouping similar products into product families based on their typologies, it is possible to narrow the spectrum of product designs and to reduce design variations.

3.3 Mass Customization in 3D Printing

As we have seen before, mass customization is traditionally related with the combination of different modules (both in position and shape), which help to achieve different constructions.

But the main difference is that 3D printing (small components and CC) attains that "Mass Customization" without the combination of modules. The customized components are made from one single piece with the combination of layered technologies. Because of this, these technologies represent a revolution in the concept and definition of "traditional mass customization".

As a result, the level of customization and personalization is even higher, especially with Contour Crafting technology. The process allows designing structures with functional and exotic architectural geometries that are difficult to realize using the current manual construction practice.

Nor it is necessary developing a common product family architecture, because the components do not have to share the any traits.

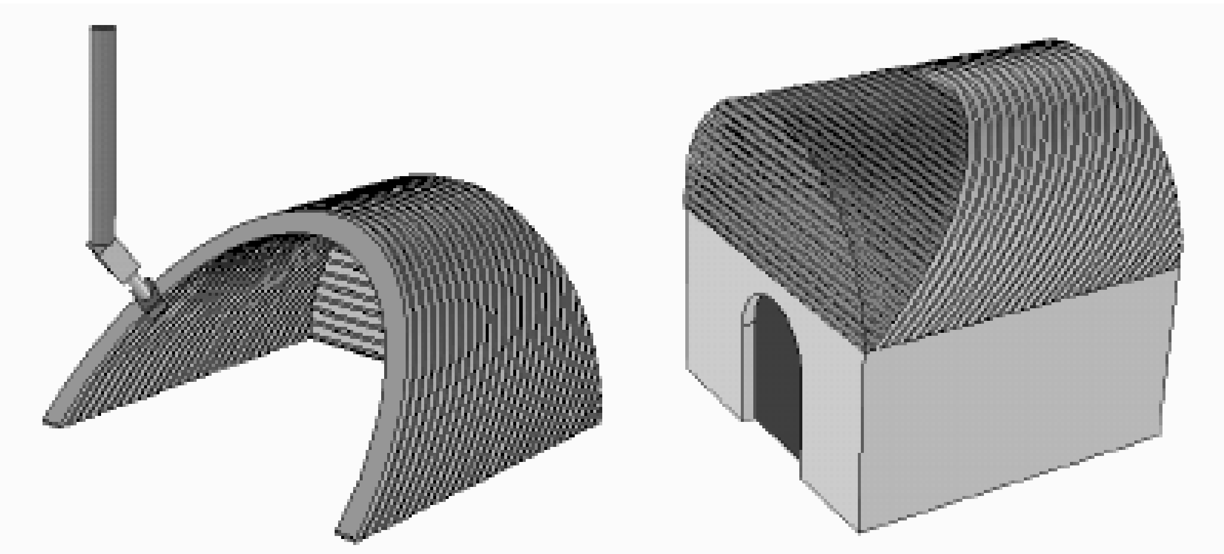


Figure 34: Supportless structures made with Contour Crafting [16]

In terms of degree of customization, there is no difference between Contour Crafting and small 3D printed components, since both permit designing with the same level of freedom.

3.4 Degree of Mass Customization of different techniques

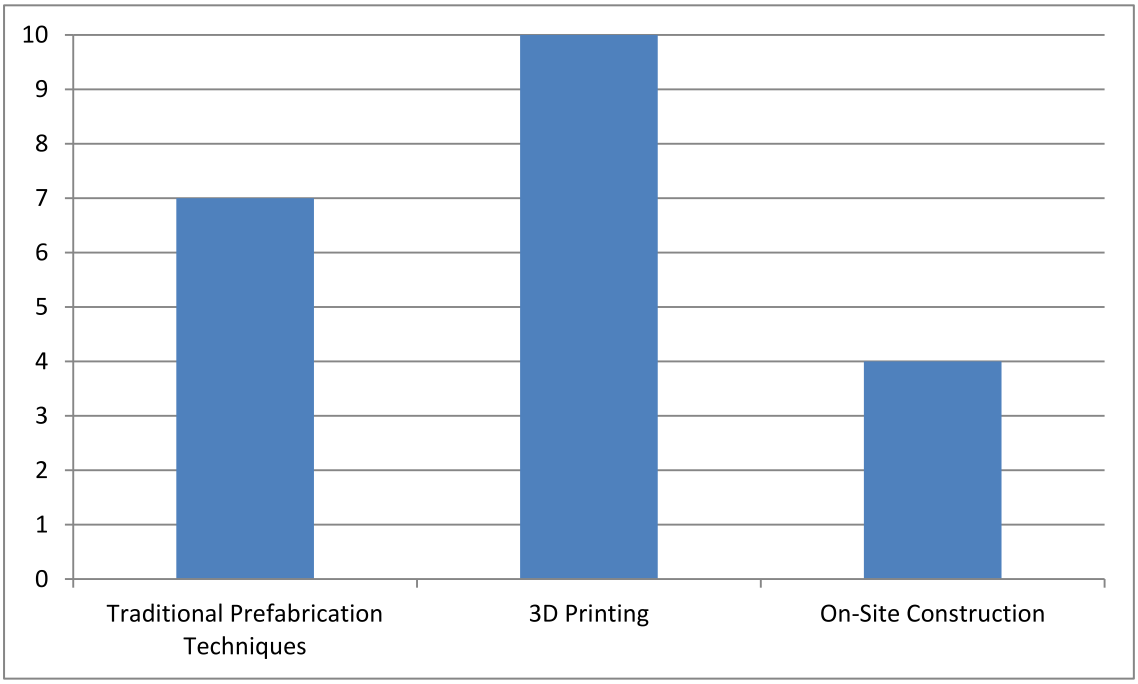


Figure 35: Degree of Mass Customization

Compared to traditional prefabrication techniques (combination of modules made with CNC) and on-site construction, 3D Printing has the highest level of customization because of the reasons exposed above.

On one side, the traditional prefabrication techniques obligate using modules and combining them to achieve different configurations.

On the other side, on-site construction techniques cannot be conceived as mass customization techniques, because companies choose between customized crafted products or standardized mass-produced ones, making customized mass-produced products impossible to achieve because of economic reasons.

Structure and Function Sharing

1. Introduction

First, it is important defining two important concepts which will be used in this text:

- Function: The function is interpreted as a specific process, action or task that a system is able to perform.
- Structure: According to Wikipedia, a structure is a fundamental, tangible or intangible notion referring to the recognition, observation, nature and permanence of patterns and relationships of entities. In this case, we are referring to an object, a built structure, which is configured by several items that have a relationship.

A method for structure sharing to enhance resource [10] [11], four categories of sharing can be considered:

- Structure sharing: More than one function is performed by the same structure at the same time.
- Function sharing: Several structures share the same function.
- Structural redundancy: Co-existing alternative structures have the same function
- Multi-mode integration: Same structure provides different functions.

In this research, I will focus mainly on structure sharing and function sharing, relating it with industrialized processes. Structural redundancy is, from my personal point of view, not interesting when building prefabricated, because all these constructions have a high degree of precision in its calculations and include an elevated safety factor.

2. Structure Sharing (SS)

Structure sharing means fulfilment of several functions by the same structure. Any product is an assembly of various components and can be represented structurally or functionally depending on the way the product is looked at.

Structure sharing (SS) relates directly to the functions and structure of the product and has a positive benefit of decreasing the use of resources; it can be negative for changeability.

There is a utility to measure the degree of SS= $\frac{Number\ of\ functions\ at\ the\ lowest\ level\ (SF)}{Structures}$ [11]. Definition of structure and functions of the product are important for the accuracy and reliability of SS.

- Main Function: Intended effects from the system at its highest level.
- Structure: any entity or feature capable of being independently identified.

How do main function and structure relate? With the FM tree: There are some simple steps we must notice to build a FM tree:

1. Identify main functions: is there is more than one MF, each will have a separate tree.
2. Identify next link: sub-function, means, organs or process.
3. Look for further branching
4. The end points of a FM ***are structures***.

The higher the number of functions per structure, the greater SS should be. Each independent function will generate and independent FM tree.

Resource effectiveness is defined as the ratio of number of structures to the number of functions these structures fulfil. RE= $\frac{Number\ of\ main\ functions\ (MF)}{Structures}$. [11]

3. Function sharing

Function sharing is the simultaneous implementation in an element of several functions by a single structural element. For a given physical and schematic description of a device, there will be a correspondence between elements in each.

<u>Function sharing must be seen as a mapping from more than one element in a schematic description to a single element in a physical description.</u>

The importance of function sharing lies in three areas:

- Designs with function sharing functionality are better than those ones without it.
- A design simplification procedure that results in function sharing allows the designer to think in modular.
- Function sharing is a new concept in the actual design, so understanding function sharing means understanding actual design.

The advantages of using function sharing are also obvious: the designs which include function sharing are less expensive since they have fewer parts; they perform better than those that do not have because decreased size and weight…

4. Structure Sharing and Function Sharing in Modules

As we explained before, a building block does not have any self-contained functionality. In order to achieve functionality, it is necessary the combination of building blocks to create a module, and then have functionality.

But obviously, not all the modules have the same degree of functionality, since both a wall and a pre-assembled service units are modules from the theoretical point of view, but the last one has to perform much more functions.

If we look at a prefabricated, pre-assembled and modular house from the structural point of view, at the lowest level we find the bricks, which are building blocks. By combining different building blocks, a module is created: a wall.

This wall is considered a non-volumetric pre-assembly component, but from the point of view of the degree of structure sharing, it has a low level since just few functions are performed by that wall. The level of function sharing is much higher compared to other types of modules because it will have to perform with other walls to be structurally efficient, to isolate the inner space from the outside, to conform a finished volumetric module...

According to what we have exposed, the combination of different walls form a modular building, which now is part of the structure and fabric of the building. In terms of degree of structure sharing, it is higher than a non-volumetric pre-assembly. Some of the functions performed only by the module are the isolation from outside, the ability to form a differentiated structure itself and an enclosed space…

The level of function sharing is lower compared to non-volumetric pre-assembly because it does not have to share so many functions with other modules: just cladding systems and common joints.

At the highest level in the pre-assembly classification, volumetric pre-assembly is found. It provides a completely finished module with one of the highest level of structure sharing possible, because above is only the complete building. Some of the functions performed by the module itself are: supporting all the loads and transferring them from the roof to the ground, providing all the necessary equipment (plumbing and electrical), the furniture…

This volumetric pre-assembly module is shaped by building blocks, non-volumetric pre-assemblies and modular buildings, all of them combined. It is obvious to conclude that the higher the degree of completion of the module is, the higher structure sharing degree and the lower the function sharing are.

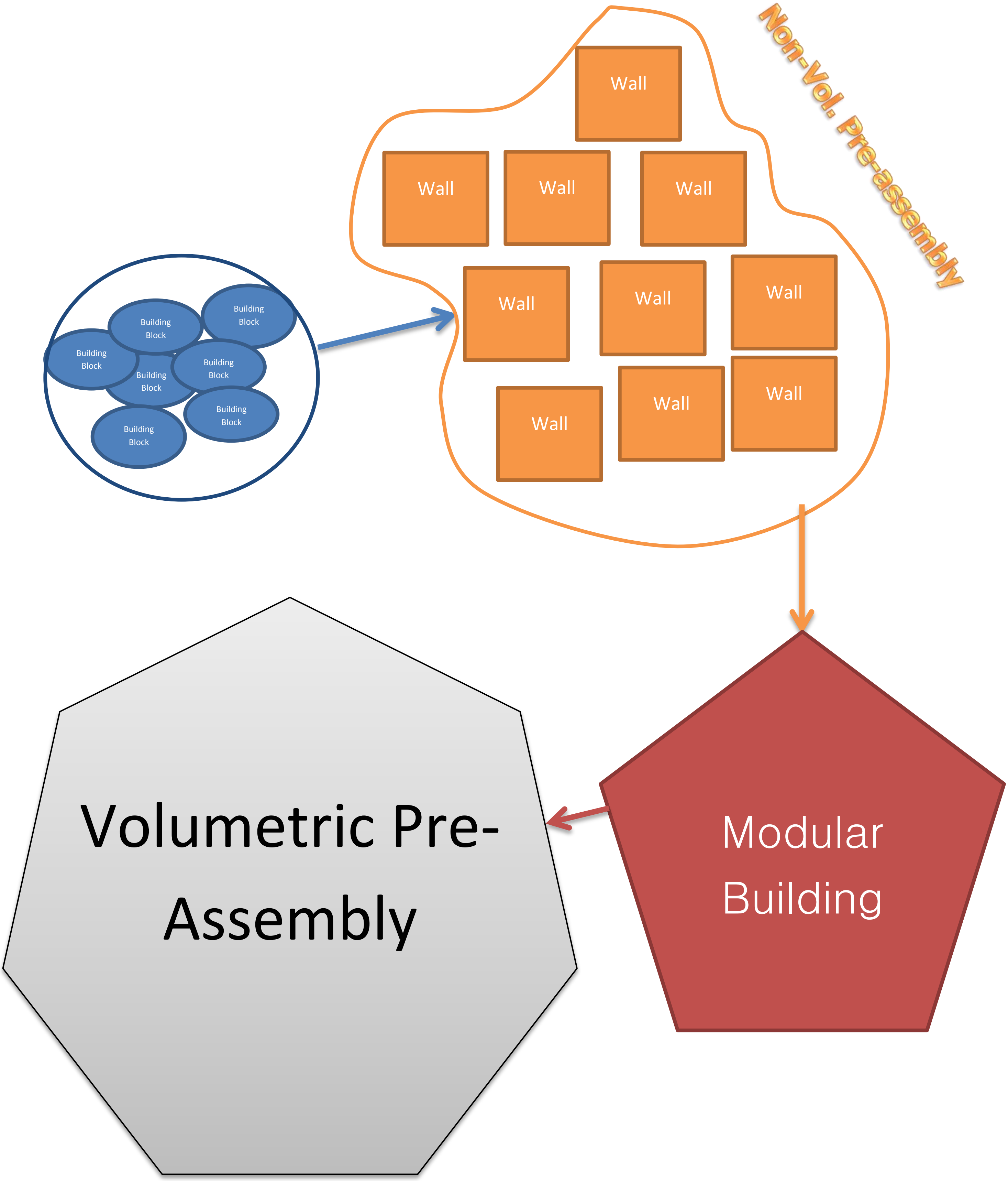


Figure 36: Graphical explanation of the combination of pre-assembled components

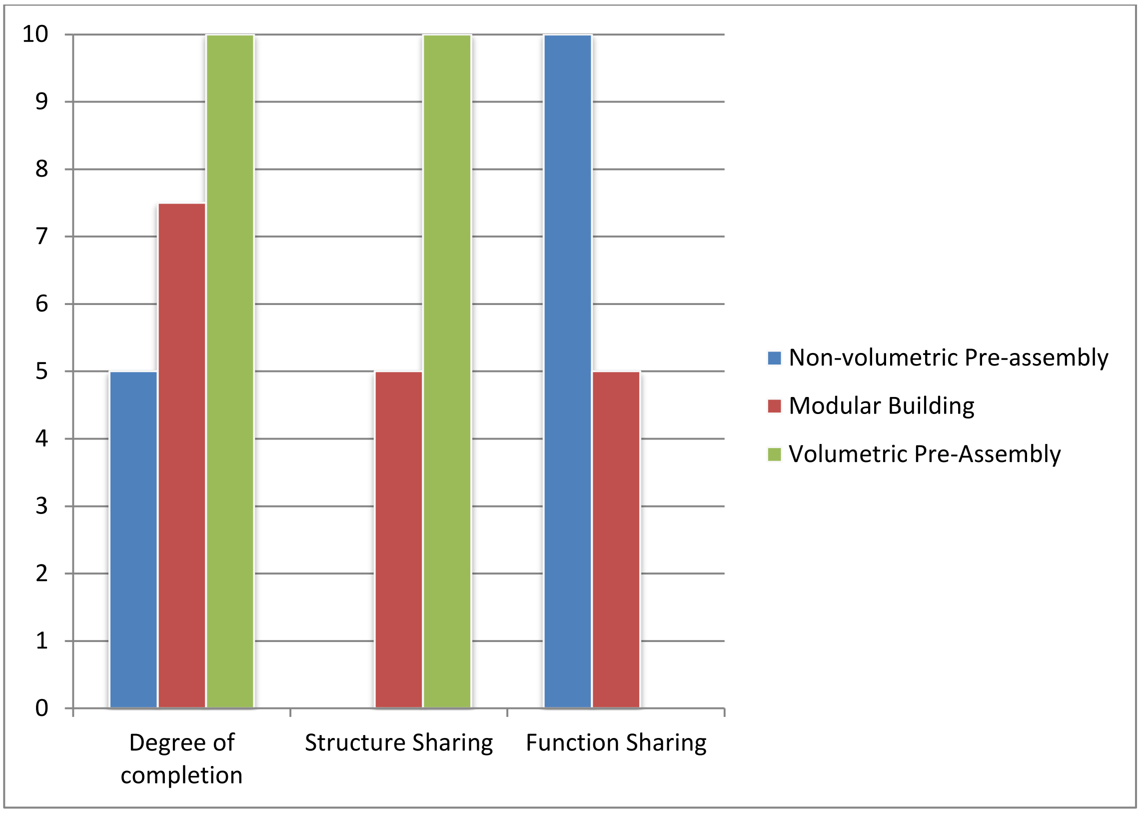


Figure 2: Comparison of different parameters in pre-assembled categories

5. Limitations of sharing

As we have seen before, it is very interesting combining sharing with prefab methods in order to achieve structural efficiency in our construction. <u>But it is also obvious that if the same element has to perform a lot of functions, it will be much more difficult to replace it in case of failure or maintenance.</u>

We can state that structure sharing principles contradict replacing ones. It may seem contradictory, because we said that for achieving that "modularity" it is necessary high level of sharing, but since traditionally buildings are not only composed by modules with high structure sharing, but also with high function sharing ones, it is necessary a "balance".

Components with high function sharing provide high flexibility and ease in case of replacement, but they also incur in higher costs, labor and complexity of the building.

<u>For building efficiently and respecting sharing and modularity principles equilibrium is required: combining non volumetric pre-assembly, modular building and volumetric pre-assembly.</u>

	Advantages	**Disadvantages**
Structure Sharing	High degree of completion Lower cost Lower labor	Difficulty to replace components
Function Sharing	Ease for replacing components and for personalization Higher flexibility	Requires much more on-site labor Costs are higher Development is more complex

Figure 3: Advantages and disadvantages of sharing variants

Case Studies

1. Boklok

1.1 Introduction to Boklok

According to "*Boklok, sweet Boklok*" (Department of Industrial Economics and Technology management, 2007), Boklok homes are ready-made, fully equipped houses and flats that consist of mostly wooden modules, which are pre-fabricated in a standardized factory-based production process. These parts are transported to the actual construction site and erected on spot usually within less than one day.

The concept of Boklok was created in Sweden in the mid-1990´s, through the collaboration of IKEA and construction company SKANSKA. In a period of just two years, the first Boklok homes were created and then exported to other countries.

Year	Progress
1997	First Boklok houses are built
2002	Boklok introduced in Norway
2003	Boklok introduced in Finland
2004	Boklok introduced in Norway
2006	Boklok introduced in UK

Figure 37: Chronology of Boklok development [19]

Boklok houses are available in 3 basic formats:

- Flats within apartment buildings
- Free standing detached houses
- 1, 2 or 3 bedroom dwellings in terraced houses.

The most typical Boklok arrangement is a two-floor block in L-shape, which has three apartments on each floor. The houses are built in a way that the exposition to sun is greater, in order to improve the efficiency. Combination of environmental-friendly materials and great isolation also helps to reduce the impact of the house. [19]

Figure 38: Typical layout of Boklok [19]

Figure 39: Boklok example [19]

In the mid-1990´s, building a prefabricated, modular, wooden house was not absolutely new, since there were a lot of companies which offered the service. The real innovation was the customer-focused characteristic of the product, as it responds to specific necessities.

As a first novelty the concept of a pre-fabricated house has been formed during the development of the idea. In order to build huge volumes of houses in an efficient way on different location, pre-fabricated parts have been a good solution. These parts are produced within a highly standardized production process, in a warm and dry environment, avoiding risks due to external factors. Approximately the 85% of the apartment is built at the factory.

Skanska developed the idea of sending huge packages to the actual construction site, like IKEA does with the furniture, and these packages are assembled by Sanska´s partners. For example, the prefabricated wooden frameworks are quite similar in all the variations of Boklok buildings. These frameworks include all the windows, plumbing and heating equipment.

Besides the substantial framework of the house, a standardized bathroom and kitchen interior is also included in the package. Resulting from the idea of pre-fabricated modules, Skanska did the effort and specified the work that has to be done by craftsmen on the site much more in detail than in other projects. The work which had to be done (plumbing, electricity and carpeting) is standardized, so the house is.

Once the modules are finished, they are loaded into the truck and delivered to the site. Then, the modules are lifted by a crane and deposited into the foundation of the building.

Finally, the finishing work is done, by connecting the wiring and the plumbing. By addition of prefab walls, the two-bedroom units can be transformed into three-bedroom units.

The homes are designed with a flexible open-plan layout, high ceiling and large windows, giving them a light feel. The costs reductions are huge by producing the standardized components and providing the suppliers all the necessary materials, instead of allowing the suppliers to buy them.

1.2 Classification in the theoretical framework

In conclusion, we have different types of industrialized components:

- Structural wooden framework
- Prefabricated components
- Complete modules

Now it is interesting classifying all these components according the theoretical framework already defined, to understand if the concepts of “prefabrication” and “pre-assembly” are coherent and aligned with that framework.

1.2.1 Structural wooden framework

The wooden framework here showed is a combination of different wooden parts which helps shaping the main structure of the module. This framework has self-functionality and can interact with other components, like the wooden walls. As a result, we can consider this framework a module.

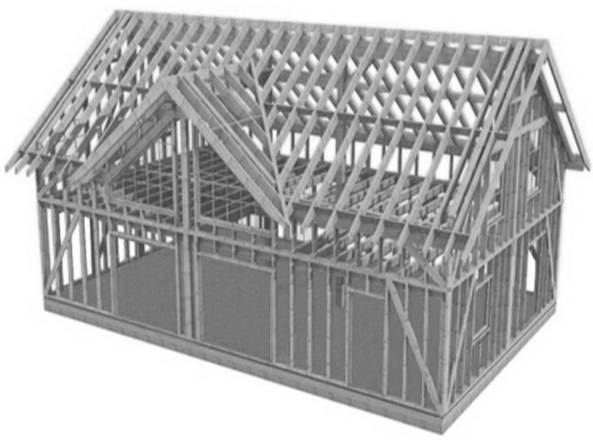


Figure 40: Wooden framework [19]

It is an industrialized process, since the framework is produced in a factory with mass production techniques. It is also prefabricated since all those components are put together at a different location. And it is also standardized because from the first stage of design it is thought to interact with other components, but the level of interchangeability may not be as high as other components (it is much more difficult to substitute the components of the framework, since removing walls is mandatory).

In the wooden framework, interchangeability is not conceived in the whole framework, but in the components of the framework.

Finally, it obviously is a pre-assembled component because the degree of completion of this framework is total. It can be considered a modular building because these components form the actual structure of the building.

1.2.2 Prefabricated components

Some examples of prefabricated components are cladding systems and wall panels, as well as door furniture, windows and all similar stuff. They are obviously made with industrialized techniques and the degree of completion is total. Since all in Boklok is conceived to be interchangeable, they meet standardization and pre-assembly requirements.

- Windows, doors and furniture can be classified within sub-assembly category and considered therefore as modules.
- Wall panels and cladding systems are non-volumetric pre-assembled components, because they do not create any enclosed space and need to be attached to the wooden frame in order to create it. According to the theoretical framework, they all are considered modules.

Figure 41: Prefab wall panels erected by a crane [19]

According to building system definition, these components are also considered as that, because they meet all the requirements.

1.2.3 Complete modules

Two types of modules can be distinguished in Boklok construction:

- The enclosed building modules, which do not include service units.
- Complete rooms

On one side, the completed building modules are a combination of the wooden framework with wall panels, ceiling systems, doors and windows. All these elements are put together in an off-site location, leaving the module ready-to-install on its final site.

The only work required in these building modules is the installation of the wiring and plumbing components, but even this work is highly standardized. Skanska provides the craftsmen the steps required for installing all the connections and the materials too, so there is no place for improvisation or changes.

On the other side, complete rooms which are later installed within the modules are also provided. These are traditionally fully-equipped bathrooms, which include the enclosures, furniture and even the plumbing.

Both types of modules are industrialized, prefabricated and pre-assembled at the highest level possible. Bathrooms are considered volumetric pre-assembly, since they create fully factory finished space and are partially independent from the structure of the building.

Enclosed building modules can be considered as Modular Building, since they form the actual structure of the building. Subsequently, furniture and other finished can be added in order to complete the module and turn it into a volumetric pre-assembly.

2. WinSun Decoration Design Engineering

WinSun, a Chinese company, has achieved building 10 houses by using 3D printing technology called "Contour Crafting". This technique is much easier to understand than traditional prefabrication methods, since all components are made with the same technique and methods.

By using a computer combined with robots or an automated crane, several layers of material are added in order to conform and create smooth accurate surfaces. This technique uses concrete as the main material to create the whole structure of the building, as well as other important components like the roof, spaces for plumbing…

Figure 42: WinSun 3D Printed House (www.winsun-pv.com/en/)

The final product is not a finished and ready-to-use product, so the degree of completion will be much lower than factory finished modules and a lot of work has to be made: windows, doors, furniture, plumbing, electrical systems, coatings…All these elements can be produced with 3D printing techniques or with traditional prefabrication ones.

If we compare it to Boklok, the Contour Crafting technology is similar to the combination of a wooden framework and the cladding panels. There is another big difference: the possibility of changing components and doing repairs.

Contour Crafting does not permit replacing one piece for another one, because transporting the cranes to the building place would be very expensive, and the structure would not resist erected without important components.

As a conclusion, Contour Crafting is a much simpler process, since it does not involve the combination of various techniques.

In contrast it provides a much less complete product compared to typical pre-fabrication techniques. During the building process it will be inevitable using manual labor in order to install all the components.

2.1 Comparison chart: Degree of completion

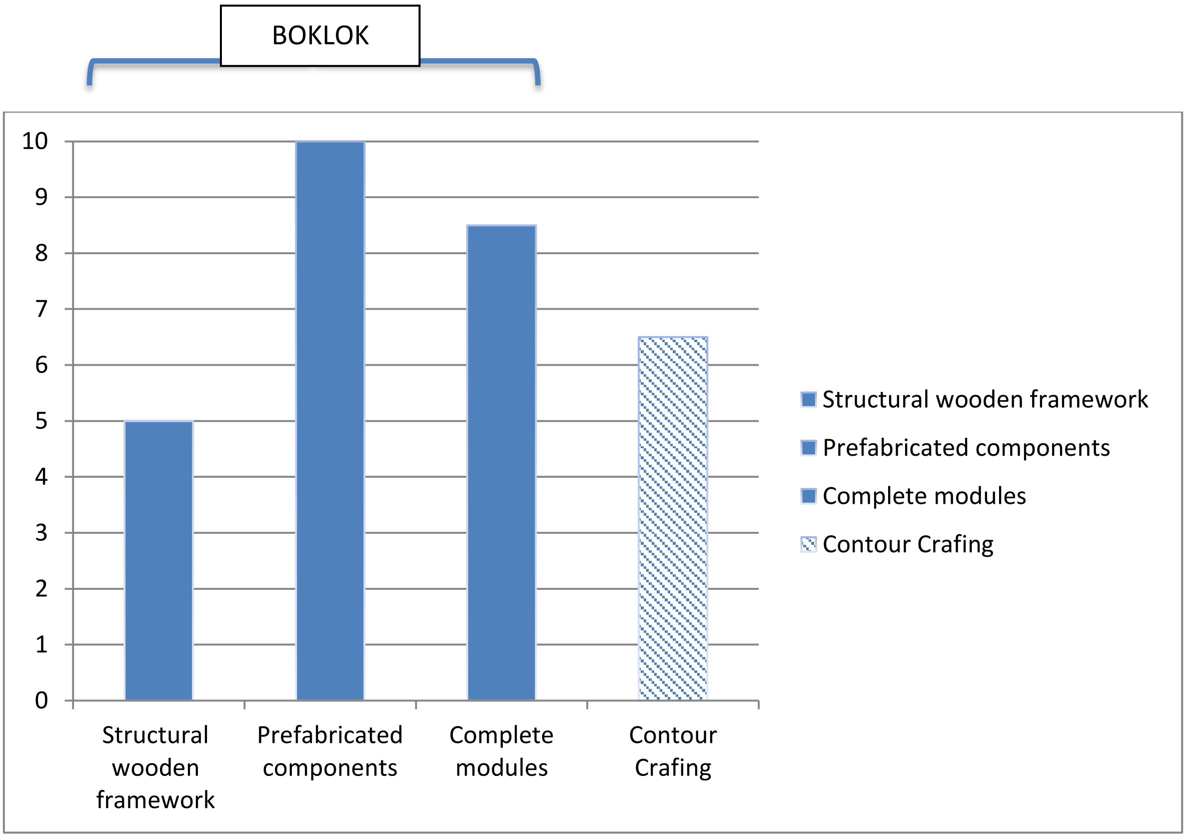


Figure 43: Degree of completion of the different techniques studied

3. Idea Builder US (Timber Framing)

Idea Builder is an American Building Company which combines the state-of-the-art digital fabrication with the use of prefabricated components, to achieve great design realizations combined with high speed, accuracy and quality.

Normally, the prefabricated materials are combined with panels to create a timber framing structure, but it may be possible employing structural concrete when desired.

The importance of 3D scanning and visualization technologies is vital, because the company does not only manufacture long runs of identical constructions, but also customizes the house according to the customer´s preferences. By using BIM, the architects, engineers and builders develop a highly accurate model which integrates different materials and components.

The different components are manufactured at offsite location, starting with the frame of the structure. This frame can be made of different materials like steel or wood and then is assembled at onsite location, so it is considered a Non-Volumetric Pre-Assembly component in the theoretical framework. At the same time, the panels are manufactured and prepared for the transportation; and they are categorized in the same level as the frame.

Depending on the feasibility of transporting all the components and installing them onsite, it is also possible combining the elements seen above (panels and frames) to achieve Modular Building components. Both options are possible, regardless of the degree or customization of the construction.

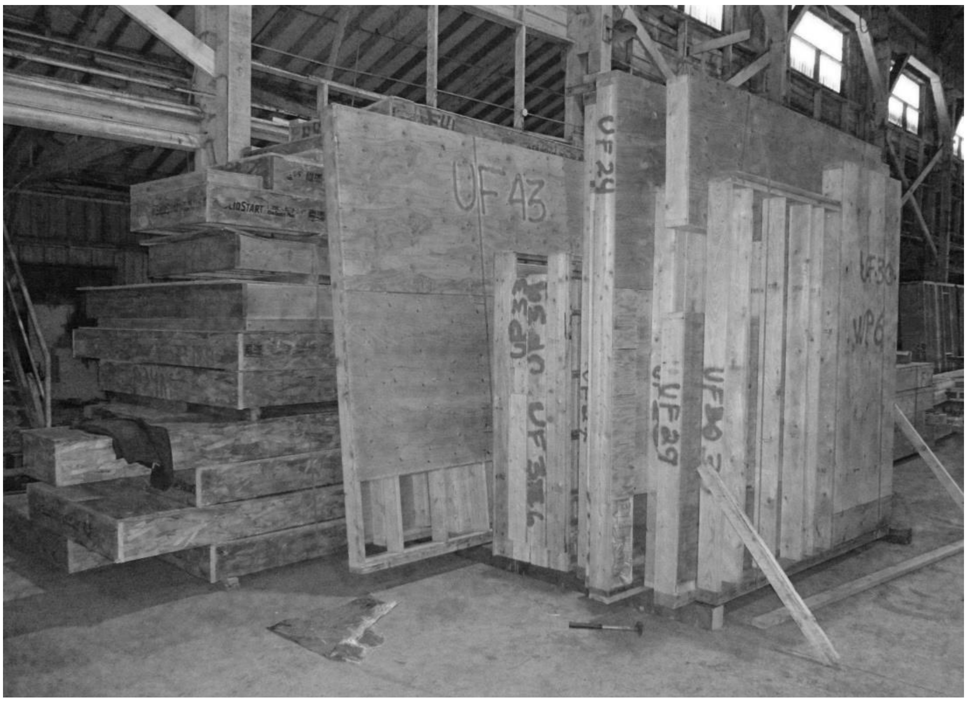


Figure 44: Panels before being transported at offsite location (http://ideabuilderhomes.com/)

The precision of the assembly is guaranteed thanks to a highly precise digital model combined with the low tolerances in manufacturing processes. These manufacturing processes are traditional ones (CNC) because 3D Printing is not yet developed enough to become the main production method. For exceptional cases when concrete is required, it is poured onsite, because producing one cast for a single project would be too expensive.

When explaining about flexible housing, the different approaches for designing a house were described, as well as “soft and hard analogy” concepts. This company is a clear example of soft analogy design, because from the first steps of design the customer is involved on it and can modify the layout depending on his preferences.

Mass customization does not have priority in the projects because the purpose is not building long-run constructions, but to satisfy the customer’s desires while maintaining a low budget with high quality.

Figure 45: Example of Prefab Construction combined with concrete (http://ideabuilderhomes.com/)

Transportation is the main inconvenient of the technology, because the highest the degree of completion of the components is, the most difficult is the transportation and the most expensive are the tools required for erecting the materials.

Because of this, it is important evaluating the convenience of producing a modular building component which incurs in lower assembly expenses but higher transportation costs, or just providing non-volumetric pre-assembly elements, easier to transport.

FINDINGS AND CONCLUSIONS

1. Research findings

As we said before, the purpose of this project is to create a framework to help developing new industrialized components in a digital world, and more specifically helping new people to understand better the basic principles which are used to build in the correct way.

This project is not directed for people with wide expertise in BIM and prefabrication, but for those ones with just few knowledge who want to enter in BIM world.

Obviously, this is a theoretical framework and only general guidelines and examples are provided, so each specific case should be studied in depth. Nonetheless, it is important considering all the findings achieved along the paper to ease the acquisition of knowledge. The different conclusions from each chapter will be presented now:

1.1 Conceptual and theoretical definitions of building concepts

The theory explained here is the foundation of the project, because all the ideas formulated later are inter-related with this. The first important concept is the concept of module and building block. <u>For an element being a module it requires these characteristics: interchangeability, self-contained functionality and interaction with other modules. That simple. Any other thing is a building block.</u>

Industrialization is the modernization process throughout new technological production methods are achieved, ensuring higher quality and faster produced products. In this industrialization environment, different degrees of completion can be achieved. <u>Depending on these degrees of completion, the different terminologies can be applied: prefabrication, standardization and preassembly.</u>

Prefabrication involves the manufacture of the different parts on a site different to its definitive location. But the element does not need having modularity or being joined to other components there.

Standardized components are those which are interchangeable. Since designing standard allows interchanging modules, it involves designing based on modularity. Pre-assembly means joining the different components at a remote location and four different types of elements can de classified, depending on the degree of completion too. <u>It is highly recommended designing based on standardization, modularization and pre-assembly principles, i.e. designing modules.</u>

The advantages of modules are less labor, higher interchangeability and modularity, higher quality and scheduling. But there is also one big reason for using modules: their principles are aligned with BIM ones.

1.2 BIM Environment

BIM is an information base which can be used throughout all the life cycle of the building and has 6 different dimensions: 3 geometrical dimensions, scheduling, cost and life cycle.

Opposite to CAD (which is a non-parametric 3D and 2D technology), it is based on parametric modelling principle: the objects know which their purpose is and why are they placed there, so the relationship between the different components is also included. The changes in the objects also affect to the rest of the elements of the structure.

It is also possible including semi-parametric objects in BIM design, especially for small objects which do not need having a close relationship with other ones. Coinciding in the idea explained above, BIM principles are aligned with modules'.

The purpose of using BIM is having a huge database with all the components offered by the different manufacturers, so that designing and estimating all the calculations in the building is a much easier process, because the components do not have to be designed in every new construction. Since using BIM and modules is mandatory, the benefits of prefabrication, modularization, standardization and BIM are all put together, leading to a highly efficient and precise process, but most important, one which reflects the reality even better.

In order to improve the efficiency of the process, the objects should be created as reusable elements, which can be employed for multiple purposes.

When designing in BIM, it is also recommended introducing firstly enclosed spaces (modular building and volumetric pre-assembly). Then, elements such as windows, doors or furniture are included, because of being part of "Building Object Models" category. Final details come with the so called "Secondary components" and include slabs, connectors and other secondary structural objects.

1.3 Building Prefabricated Components: 3D Printing and CNC

We have seen first the theoretical and then the virtual environment, and the constraints and recommendations for designing. Now the natural step is looking at the real world and at the different techniques available for building those modules.

The first technique is 3D printing, which is a combination of technologies known as "additive manufacturing", based on the addition of several layers of material, one after one. Although the technology is at an early stage, huge improvements have been done in last years.

Three different uses are distinguished for 3D printing in building industry:

- Prototyping: Most extended one, used for presenting the models.
- Small Building Components: Created with small and traditional 3D printers. All they are modules. Employs plastic and metal at the moment.
- Big Building Components: Designed with Contour Crafting technology. It is not mandatory for them being modules, because since this technology is at an experimental phase and nothing can be stated. Logic says that it will evolve to manufacturing in off-site location because of the better conditions for concrete setting. As a result, the components could also be considered as modules.

At this moment, lots of investment and research is needed for implementing 3D printing technology in construction, but worth it, since it is the clearest link between the virtual world and the real one.

The traditional techniques for creating components from virtual environments are the most used in this moment due to its maturity and can be classified in: CNC technology, molding and fastening.

<u>From an industrialization point of view, 3D printing is the best choice, because the degree completion of the component is the highest possible, since a complex component can be manufactured from a single piece of material. The purpose of BIM is achieving simplicity, and efficiency combined with quality, and those principles are totally aligned with 3D Printing technology.</u>

1.4 Buildability, Flexible Housing and Mass Customization

1.4.1 Buildability

Buildability is the philosophy throughout assembly problems are detected, making easier the design and construction of the product without using standardization or simplification of the model.

Several times has been affirmed that BIM and prefabrication help improving the efficiency of the construction process, but it can be improved to a greater degree by introducing buildability philosophy principles.

In terms of design, three generic guidelines are employed:

- Using simple shapes with low perimeter/floor area ratio, leading to a reduction in material and labor.
- Considering the placement of services or structural system in a logic position.
- Employing efficient construction methods

Further recommendations for designing according to buildability are also provided in the full chapter, not only in the design phase itself, but also in detail and concept phases. BIM itself does also align with buildability principles, because it permits exploring and measuring the space much better and detecting possible incompatibilities or clashes in the drawing.

1.4.2 Flexible Housing

Related with buildability, it is provided a wide description of advices for building with different materials, from steel to concrete.

Construction industry has never been characterized by adapting quickly to changes or introducing novelties. It has always been very rigid in terms of layout’s flexibility. Because the possibility of changes in housing needs throughout its lifetime, another way of constructing is required, and prefabrication combined with BIM provides the opportunity to set new benchmarks in terms of flexibility.

Because of that, four different flexibility-related strategies have been studied, depending on the desired approach given by the designer:

- Design for disassembly: Used in prefabricated elements manufactured in a factory, which are later joined all together onsite and can be easily disassembled. Building units may be inserted or removed over the time to accommodate changes.
- Design for reuse: Standard forms and modules can be reused easily if they are in good conditions. It is easier identifying recyclability of materials when they are produced offsite.
- Design for temporality: Site buildings or supportive emergency housing are fine examples of temporality.
- Design for change: As we said, necessities of people change throughout the lifetime. Because of that, giving the chance to introduce modifications is essential. These modifications can be determined by the users (giving a higher degree of freedom) or by the designer (constraints are introduced and not all the modifications can be introduced).

But flexibility does not only have to be restricted to the modification of the building once built; the availability of different choices and layouts before being built is also flexibility.

Designing flexible is not omissible, because prefabrication and BIM principles are closely linked to flexibility and modularity. It helps not only the maintenance of the building, but it is also good for manufacturers, because they ensure that the customers will be satisfied with the product and will buy the accessories to achieve the combinations in case of demand.

1.4.3 Mass Customization

I stated before that flexibility can be achieved through two ways: by providing ways to modify the building once built or by satisfying the requirements of the customer before being built. In that case, mass customization is really useful because permit achieving unique products with cost-efficient manufacturing methods.

For getting a high degree of mass customization, customers should be involved in the early design stages of the building. There is even a design philosophy called DFM (Design for Mass Customization), which provides come advices about this type of design and introduces the concept of “Family-based design”.

Traditional mass customization principles are based on the combination of modules in different ways to achieve different shapes, but with the appearance of 3D Printing technology those different shapes can be achieved from a single piece of material.

This leads to a new world of possibilities, permitting the degree of personalization to reach higher benchmarks combined with economical budgets. This reason is enough for making highly recommendable introducing 3D printing in construction and researching for making its use standard.

1.5 Structure and Function Sharing

Structure and Function Sharing concepts are interrelated with flexible housing and it is obvious the reason: structure and function sharing help to measure the degree of relationship of the different components and how they group to develop the functions.

In the correspondent chapter, I concluded that the degree of completion is directly proportional to Structure Sharing degree and indirectly proportional to Function Sharing degree. When several functions are performed by the same structure, the costs can be reduced hugely but modularity is negatively affected.

Because of this reason, <u>it is recommendable maintaining an intermediate level of structure and function sharing by using “Modular Building” components, instead of volumetric pre-assembly, whose degree of completion is higher.</u>

<u>It is obvious concluding that the highest the degree of completion of a component is, the most efficient it is, but at some point, modularity is compromised and that point should not be overpassed.</u>

1.6 Case Studies

We have seen three different examples of case studies with different used techniques. We have agreed that when designing prefab components in BIM these characteristics should be included: module, prefabrication, standardization and pre-assembly. All the examples include these characteristics.

What distinguish the different cases is the degree of completion of the components provided by the manufacturer and the customization available. Boklok houses entail all the modules’ characteristics but the possibility to introduce changes is reduced, because the processes are rigid.

WinSUN on the other side achieves speed and customization when building the concrete structure, but for the installation of the rest of the house traditional prefabrication methods are necessary, so the advantage taken while building the structure is not so high.

Idea Builder provides both customizations in materials and design but cannot achieve produce completed modules, so greater amount of labor is necessary.

It has been said that the balance is in the middle point and for that reason WinSUN is the represents more clearly the principles exposed, by combining:

- Usage of modules
- Mass customization
- Buildability techniques
- Usage of BIM

2. Conclusions and future work

From the first moment, my ideas about construction's state of technology have been clear and researching deeper about them has not only confirmed my initial thoughts, but I have realized that a big revolution is necessary. And precisely, the introduction of BIM and may become the tool to revolutionize this old-fashioned industry. The ideal way of construction should have these characteristics:

- Using modules, combined with prefabrication, modularization and pre-assembly principles
- When designing, using parametric models and including as much information as possible related with the model
- Combining BIM with prefabrication in every case
- Explore new ways for creating building components if its use involves less onsite labor. 3D printing is a clear example of an early technology which can revolutionize the environment.
- Dynamism in building components, from a situation where houses' layouts and configurations are static to another one where they can adapt to everyone's desires.
- Efficiency by combining lean build techniques and principles

From the lowest level, the use of modules is the initial starting point for my recommendation: they are interchangeable and can be combined and perform with other components. Obviously this entails prefabrication, pre-assembly and modularity, and that is the way in which components should be designed for achieving wider benefits.

But creating components through industrialized processes is not an easy job. A big industrial infrastructure and expertise is required for creating a high-tech complexes where producing these elements. This may be a pitfall for not highly-developed countries, with cheap and abundant labor force.

Factories are usually placed at the outskirts and transportation of materials to building place is sometimes difficult and may not be possible if the road is congested. Another ways of transport like train are not either always accessible. Because of this, sometimes it may not be possible implementing prefabrication processes in all the cases.

BIM is a technology which is used not only for designing, but also for maintaining and calculating all the efforts in the building. Because documentation available is much higher in prefabricated components, it is naturally easier including them in the BIM environment. Besides, when components are produced under strict conditions, it is easier avoiding possible construction problems or inefficiencies.

But using BIM also has limitations, like the higher level of expertise and qualification of the designers required, or the inevitable collaboration between architects and engineers, which sometimes is not as easy as desired.

Using modules is important, so are parametric characteristics within the drawing. There are several possibilities for introducing elements in BIM environment, but using parametric and semi-parametric elements is the recommendable choice.

Modules have intrinsic interchangeability by definition, and parametric characteristics make the object even smarter by changing the way objects behave between themselves. For that reason, when possible, it is convenient using parametric objects and only when working with small and non-relevant elements, using semi-parametric entities (basically consists on introducing not as much information as parametric objects).

But sometimes the problem is not designing the building, but the manufacturing process for creating the components. I truly believe in modularity and interchangeability as the path for constructing in the future. For that reason, a manufacturing technique which offers a clear link between the digital and the real world is highly desirable. When exploring the state of the technology, traditional techniques entail the use of CNC machinery, but also molding or fastening when working with other materials.

With these techniques, the degree of finish is high, but sometimes big modules are composed of many sub-components, leading to higher costs and efforts. Opposite to traditional techniques, 3D printing permits creating complex components from one single piece of material while achieving complex shapes which would be impossible with traditional methods. This is especially remarkable if the material is concrete.

Casts are expensive to produce and it is necessary the combination of several of them to get precast elements. Contour Crafting is a huge revolution because simplifies the process by eliminating the need of having a cast and introducing robots. First tests have been made at onsite location, but since the technology is not yet fully defined, there are too possibilities of producing offsite components, which is also sensible (setting of concrete is better when external conditions are highly controlled, like in a factory).

Again, implementing this technology may be expensive and risky, but as I stated before, it is the clearest link between the digital world and the real one and to be coherent with the principles defended along the paper, and I highly recommend its implementation. The popularization of this technology may not satisfy manufacturers due to the possibility of acquisition of 3D printers by the consumers and self-production of the components, and this is the biggest inconvenient at the present moment.

I also talked about dynamism, referring to avoid static layouts which limit the flexibility of the construction. Flexibility and modules are intrinsic concepts, but is highly recommended techniques for improving that flexibility. Of course, when modules are used they can be substituted in case of failure, but they do not have to be accessible, making reparations more difficult. For that reason, knowing the desires of the customers and using flexible housing principles is one of the best options for achieving desired modularity.

Sometimes, architects, designers and engineers focus in making impressive designs, downplaying functionality which should the greatest objective when constructing houses.

But it is possible maintaining three principles which are usually opposed: (functionality, price and customization) through the application of mass customization principles.

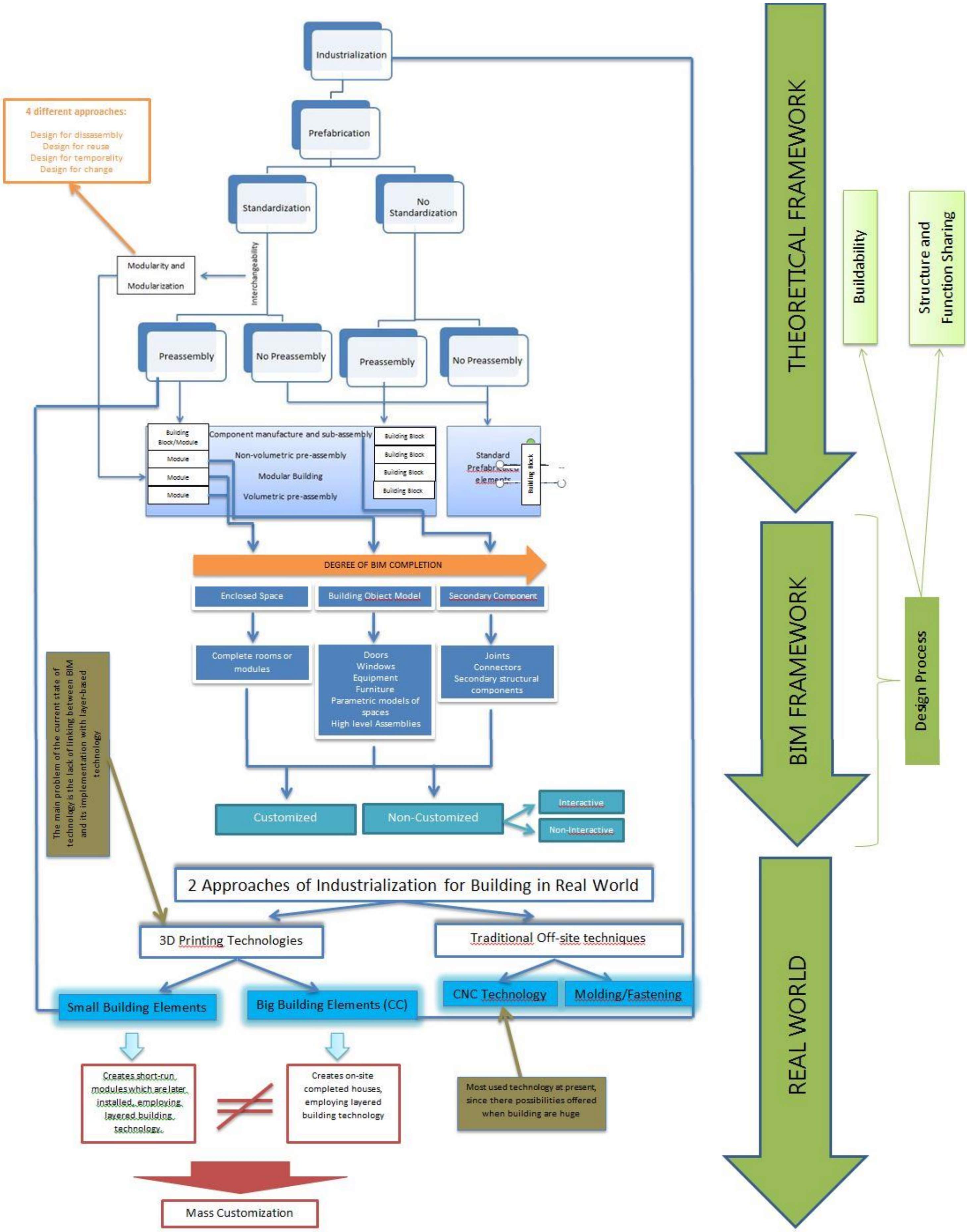
At this moment, there are several concepts (mass customization, buildability and flexible housing) whose potential can increase thanks to the use of prefabricated modules and BIM. Exploiting this potential should be a priority for every designer for creating a new way of understanding the relationship between customers and manufacturers.

<u>My final conclusion is that the necessity of introducing prefabrication in construction is obvious because of all the advantages stated before, although it is difficult to explain the benefits of modularization or flexible housing, especially when those concepts cannot be measured. For encouraging constructors adopting these technologies, long-term benefits should be presented, with special attention to the cost (most influent factor in building projects) and quality (for being the most reluctant factor for customers).</u>

This project is a starting point for those people who are not familiar with BIM and prefabrication, but it is not a technical paper with specific recommendations for BIM software (TEKLA, REVIT...).

Therefore, if someone would be interested in continuing the topic, I would propose researching in the technical aspects of the software and giving a fully detailed guide for designing parametric objects according to the advices given.

By rewriting the framework more academically, it could be used too for teaching purposes for Civil Engineering students, providing a great opportunity to expand BIM knowledge and research.



Industrialization
Prefabrication
Standardization
No Standardization
Interchangeability
Modularity and Modularization
4 different approaches:
Design for dissasembly
Design for reuse
Design for temporality
Design for change
Preassembly
No Preassembly
Preassembly
No Preassembly
Building Block/Module
Module
Module
Module
Component manufacture and sub-assembly
Non-volumetric pre-assembly
Modular Building
Volumetric pre-assembly
Building Block
Building Block
Building Block
Building Block
Standard Prefabricated elements
Building Block
DEGREE OF BIM COMPLETION
Enclosed Space
Building Object Model
Secondary Component
Complete rooms or modules
Doors
Windows
Equipment
Furniture
Parametric models of spaces
High level Assemblies
Joints
Connectors
Secondary structural components
Customized
Non-Customized
Interactive
Non-Interactive
The main problem of the current state of technology is the lack of linking between BIM and its implementation with layer-based technology
2 Approaches of Industrialization for Building in Real World
3D Printing Technologies
Traditional Off-site techniques
Small Building Elements
Big Building Elements (CC)
CNC Technology
Molding/Fastening
Creates short-run modules which are later installed, employing layered building technology.
Creates on-site completed houses, employing layered building technology
Most used technology at present, since there possibilities offered when building are huge
Mass Customization
THEORETICAL FRAMEWORK
BIM FRAMEWORK
REAL WORLD
Buildability
Structure and Function Sharing
Design Process

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Title	Author	Date	Main Ideas in the document	Useful concepts for the research
Defining Modules, Modularity and Modularization	Thomas D.Miller/Per Ergard	1998	Evolution of the concept of behind modularization throughout the years Requirements to define modules compared to building blocks Definition of module, modularity and modularization	Examples of modules compared to components and systems Definition of modules, modularity and modularization
Prefabrication and Preassembly: Trends and effects on the construction workforce	Carl T. Haas/James T.O'Connor/ Richard L.Tucker/ Jason A. Eickmann/Walter R.	2000	Determine prefabrication and preassembly trends and effects on the construction workforce	Theoretical definitions of building concepts, such as preassembly, industrialization and Modularization
Standardization and Pre-assembly; Distinguishing myth from reality	G. F. Gibb	2001	Discussion of the past, present and future applications and key benefits of standardization and pre-assembly	Types of pre-assembled elements according to the author
A classification system for representation of off-site manufacturing concepts through virtual prototyping	Abosaod, H./Underwood, J./Isikday,U./Barony,S.	2006	Study of virtual representation system for UK housing according to qualitative and quantitative housing deficiencies	Off-site manufacturing related terminologies and definitions
The essential characteristics of industrialized building system	W.A.Thanoon/Lee Wah Peng/Mohd Razali Abdul Kadir/Mohd Saleh	2003	Replacing the former system by a new Industrialized Building System (IBS) which	Understanding the definition of Building System, as well as the different types of

	Jaafar/Mohd Sapuan Salit		has immense inherent advantages	Building Systems available
Re-engineering through pre-assembly: client expectations and drivers	G. F. Gibb/Frank Isack	2003	The paper presents the results of an interview survey of major construction clients regarding their expectations from and drivers for pre-assembly on their projects	Specific definition of Pre-assembly Types of pre-assembled components and how are they classified Descriptive figures in order to understand the concepts more clearly
Prefab Architecture: A guide to modular design and construction	Ryan E. Smith	2010	Large explanation of prefabrication from several points of view: -Context -Applications of prefab materials (including fundamentals, elements, assembly principles and sustainability) -Case Studies	Principles for using prefabrication Comparison of many aspects of onsite and offsite fabrication Structure of Prefabricated elements Types of prefab materials, components, panels and modules Assembly advices and modularization ideas
Industrialization of construction-A lean modular approach	Anders. Björnfot/Lars Stehn	2005	The paper is based on a literature review of modularity, lean construction and buildability. Tries to explain the differences and inherent concept of each terminology.	Definition of modularity, lean construction, buildability, DFM and DFA
Revista Ingeniería de Construcción	Universidad Católica de Chile/ Escuela de Ingeniería/ Departamento	1997	Approach for prefabrication, pre-assembly and modularization (PPM)	Prefabrication, pre-assembly and modularization concepts.

	de Ingeniería y gestión de la construcción		concepts from a theoretical point of view	
A new approach to structure sharing	Amaresh Chakrabarti	2004	New approach for supporting structure sharing in design that has been implemented into software for automatically creating and offering a variety of alternative principles	Basic principles and of structure sharing
A method for structure sharing to enhance resource	Amaresh Chakrabarti/Vishal Singh	2007	Define concepts of function and structure, and using them to define SS and RE Compare definitions Develop a method for assessing and enhancing RE Evaluate this method for its effectiveness	Different categories of sharing Definition for structure sharing and the method for calculating it FM tree concept Resource effectiveness definition and method for calculating it
3D Printing: Technology and Beyond	Mathilde Berchon/Christina Wainikka/ Waldemar Ingdahl/Per Strömbäck	2013	First approach to 3D printing from it´s historical point of view Analysis of the current situation Different techniques available for 3D printing	Basic explanation of each technique available for producing components
3D printing and the future of manufacturing	Leading edge forum: technology program	2012	The rise of 3D printing: from the professional industry to the home-user.	Advantages of 3D printing. The actual state of this technology An approach of how the technology will be supposed to evolve

BIM Handbook: A guide for Building Information Modelling for Owners, Managers, Designers, Engineers and Contractors	Chuck Eastman/Paul Teicholz/Rafael Sacks/ Kathleen Liston	2011	The aim of the book is providing a thorough and consolidated reference to help students and practitioners in the construction industry in all the aspects of BIM	Explanation of BIM principles. Definition of what is BIM and what is not. Benefits of BIM Distinction of what is BIM and what is not. Difference of constructability and design model. Ways of improving constructability in four different components: concrete, steel, curtain walls and services.
Use of BIM for constructability analysis in construction	Hui H-Suan Yang/Meng-Hsing Lee/Fu-Cih Siao/ Yu-Cheng Lin	2013	The paper shows how application of BIM approach in building helps improving the constructability. Some procedures for constructability are proposed using BIM technology	Understanding the dimensions in which BIM will helps with constructability
Automated Construction using Contour Crafting-Applications on Earth and beyond	b. Khoshnevis/George Bekey	2007	Definition of Contour Crafting, tools required for using this technique and applications in construction	Definition of Contour Crafting Benefits of using this technique

Buildability and constructability: a literature review	Unknown	Unknown	The paper places emphasis on conceptual guidelines for buildability implementation. Also concentrates on knowledge management in buildability with respect to how information is classified.	Definition of buildability and constructability, and historical evolution of the concept.
Characteristics of Design-relevant constructability knowledge	Martin Fischer/ C.B. Tatum	1996	Examining the current project delivery process, the paper recognizes factors which tend to inhibit the construction constraints during design and observed conditions which require increased constructability input.	General tips for constructability from design point of view.
Boklok, sweet Boklok	Victoria Gomez Quesada/Claudia Idone/ Norman Meuschke/ Nicolas Teboul	2007	The paper presents the concept for functional, low-priced and pre-fabricated houses made in collaboration of IKEA and SANSKA	Types of apartments available with Boklok Definition of Boklok Historical review from the beginnings to the actual moment
Flexibility in multi-residential housing projects: three innovative cases from Turkey	Duygu Albostan	2009	The thesis discusses flexibility and the related concepts in the context of housing, by focusing in three innovative multi-residential projects in Turkey.	Flexibility and flexible housing concept. Soft and hard analogy Areas of innovation in flexibility

Flexible Housing: The means to the end	Jeremy Till/Tatjana Schneider	2005	The paper explores flexibility and modularity through the issue of "soft" and "hard" analogy	Ideas about the different approaches for designing buildings
Design for Mass Customization	Mitchell M.Tseng/ Jianxin Jiao	1996	Mass customization main principles. Product family architecture features and formulation.	Technical challenges of Design for Mass Customization
Parametric Building Modelling: BIM´s Foundation	Autodesk	2007	Explanation of parametric building concept and the reasons for using it.	Definition of parametric Modelling
BIM Content Development: Standards, Strategies and Best Practices	Robert S. Weygant	2011	The idea of the book is to assist all parties in developing and leveraging appropriate BIM content. Includes references about best practices and principles applied to BIM.	Non-parametric and semi-parametric objects within BIM framework